of a great beam hung the pump rods ; at the other hung a piston working in a cylinder, the cylinder being closed at the bottom and open at the top. The action of the engine was simple in the extreme. The cylinder having been filled with steam from a boiler beneath it, a spray of water was admitted to condense the steam and to form a partial vacuum. When this had been accomplished, the atmospheric pressure caused the piston to descend, thus raising the pump rods.

After the erection of the Dudley Castle engine in 1712, others were set up in Cornwall, Flintshire, the Newcastle-upon-Tyne area, London, Königsberg, Cassel, Paris, and in Sweden. No patent was ever taken out by Newcomen, but Savery's patent was considered to cover Newcomen's plan. The method of working naturally resulted in a great expenditure of fuel—about 25 lb. per horse-power

per hour—but engines of the type were made until the beginning of the nineteenth century, and one or two were at work within the last twenty years.

The first great improvement in the engine came with Watt's experiment with the Newcomen engine model, still preserved at the University of Glasgow, which led to the invention of the separate condenser in conjunction with an air pump, a system which, as is well known, is still used in all condensing engines.

For a very long time Newcomen's merits were but little recognised. The Dartmouth antiquary, Thomas Lidstone, in 1857, and again in 1873, advocated the erection of a memorial to him at Dartmouth, and the project was at last carried out in 1921, the memorial consisting of a block of Dartmoor granite on which is a bronze plate with a line drawing of Newcomen's engine and an inscription.

Some Problems of Cosmical Physics, Solved and Unsolved.¹

By Lord RAYLEIGH, F.R.S.

THE NEBULAR AND AURORAL SPECTRA.

AFTER the first period of success in identifying the origin of the spectral lines of the sun and stars with terrestrial materials, certain outstanding cases remained which were obviously important, but in which the identification could not readily be made. The first of these cases to yield was that of helium, which was unravelled while some of the pioneers in astronomical spectroscopy were still active.

Kindred to the hypothesis of helium, so triumphantly vindicated by terrestrial experience, were the hypotheses of nebulium, geocoronium and coronium. The problems epitomised by the two former words have now been solved, though the solution has taken quite a different turn from what was expected by the older generation of astrophysicists.

In the nebulae are spectrum lines which have never been observed terrestrially. These are not faint members of otherwise complex spectra, such, for example, as we have in nearly all remaining unidentified lines of the solar spectrum, but they stand out, bold and challenging, on a dark background, presenting a puzzle that was the more intriguing from its apparent simplicity. According to spectroscopic experience, now made precise and rational, simple spectra are due to light elements. This, taken with the fact that lines known to be due to hydrogen and helium accompanied the nebular lines, strongly suggested that they too were due to light elements of the class which terrestrially are known as permanent gases. But the fact remained that no one had succeeded in observing them in the laboratory, and as time went on the originally convenient resource of relegating them to an unknown element had become less convenient. For the scheme of the elements became definite, and there was no room in it for new light elements.

More systematic knowledge of spectra in general, and of the spectra of the light elements in particular, was wanted before the question could be resolved. The clue was afforded by the circumstance that important nebular lines occur in pairs, obviously associated by their closeness and their constant relative intensity in different nebulae and in different parts of the same nebula.

It is found, then, that the frequency difference of the green pair of lines originally discovered by Huggins, and known as N_1 and N_2 , is 193 waves per centimetre. I. S. Bowen, to whom we owe the final elucidation of this enigma, sought for an equal interval in the spectrum of doubly ionised oxygen which he was analysing, and found it in the interval between the low-lying levels designated as P_2 and P_1 . The lines were attributed to intercombination between one singlet upper level and two lower levels belonging to a triplet, the third being excluded by the rule of inner quantum numbers. To fix the differences of the terms concerned, it was necessary to connect the singlet and triplet levels by an intercombination line observed in the laboratory spectrum of doubly ionised oxygen. This was done by A. Fowler, who, combining Bowen's laboratory data with his own, was able to get a fairly satisfactory check on the observed position of the nebular pair. Practically no doubt remains, in view of the fact that other less well-known nebular lines can be similarly explained as due to singly ionised nitrogen and singly ionised oxygen.

The identification of these lines was made by ignoring so far as convenient the rules of the quantum theory. These rules forbid certain lines which might occur according to the combination principle. When a state of excitation of the atom is such that it cannot directly pass to a lower state without breaking one of these rules, that state is called metastable ; and this is the case which we have in the nebular lines.

The next cosmical problem I wish to refer to is the long outstanding one of the green line of the

¹ From the presidential address to Section A (Mathematical and Physical Sciences) of the British Association, delivered at Cape Town on July 24.

aurora, which was first seen by A. J. Ångström at Upsala in 1868. In this case the enigmatic line is even more isolated than in the case of the nebulae, since, except in the case of unusually bright auroras, one can see nothing else in the spectrum at all. An apparently exhaustive study of the spectra to be obtained from terrestrial gases by the combined efforts of very many experimenters gave no clue to its origin.

The clue was eventually found by McLennan, who was able to produce the line by heavy electric discharges in a mixture of oxygen and helium, or, better, oxygen and argon. Oxygen is essential, and there is now no doubt that the aurora line is an oxygen line. There is, however, yet more to be done, for we do not know how to get the green line alone or with only the negative nitrogen bands as we see it in the sky. In the artificial spectrum the ordinary oxygen lines and the lines of the inert gas, helium or argon as the case may be, are conspicuous.

The wave-length of the auroral line could not be foreseen or calculated from our present knowledge of the arc spectrum of oxygen. In this case we have only a single line to deal with, and are thus without the invaluable clue afforded in the case of the nebulae by the frequency separations of a doublet or triplet. There is, however, no difficulty in finding a conjectural place for it in the scheme of the oxygen arc spectrum as given by Hund's theory.

McLennan, arguing from the fact that nitrogen bands do not appear in the spectrum of the night sky, which, however, shows the green line, takes the excitation potential as less than 11.5 volts. This condition excludes very many possibilities. Indeed, if we are to be bound by the selection rules, it excludes *all* the possibilities. So with the example of the nebulae before him, McLennan waives these rules, and assigns the green line to a transition from one or other of the low-lying metastable states which the theory indicates.

The lowest state of all should be a triplet, and owing to the absence of companions to the green line this may very probably be excluded. If so, only one alternative remains, and the successful determination of the Zeeman effect carried out in McLennan's laboratory is in harmony with the choice so arrived at. An independent investigation by L. H. Sommer, published immediately afterwards, covered exactly the same ground, and led him to the same choice. For the auroral line we have the experimental production from oxygen, but not the numerical spectroscopic relation. For the nebular lines our position is exactly the reverse.

There are other features of the auroral spectrum which are still obscure. I will limit myself to discussion of one of them—the red line of the aurora. Red aurorae are comparatively rare, and when they do occur the distribution of colour presents very curious features. In some cases the ends of the streamers are tipped with red, while the greater part of the length is green. The only reddish aurora which I have been privileged to observe at my home in the south of England (May 14, 1921) was of a

different character, the colour ranging rapidly through various shades of purple. The light was distributed in irregular patches high up near the zenith, though predominantly in the north. At the same time its position was highly unstable, and the general impression produced was reminiscent of high potential discharges in highly exhausted vacuum tubes. Vegard has described cases where the whole sky suddenly turned crimson. He has obtained good small-scale spectrograms of the red line, which give the position as $\lambda 6322$. A determination by V. M. Slipher of the Lowell Observatory gave $\lambda 6320$.

So far as can be judged from the evidence available, no pair of the low-lying levels of the oxygen arc scheme which McLennan has discussed in connexion with the aurora are suitably placed to yield this red line by combination. We naturally turn to the consideration of nitrogen spectra, which, as is well known, are represented in the blue and violet regions of the auroral spectrum.

I described in 1922 a spectrum in which one of the first positive bands of nitrogen, $\lambda 6323$, was very much intensified relative to the neighbouring red bands, which ordinarily are of comparable brightness. This spectrum was produced by adding a large excess of helium to the nitrogen afterglow, and the source had a visual red colour dominated by this band. In describing this work it was suggested as a possibility that this was the origin of the red auroral line, and somewhat similar ideas have been revived by McLennan in his recent Bakerian lecture. But there are difficulties to be met. One of the most urgent problems in auroral work is an adequate wave-length determination of this red line from a large-scale spectrogram.

EXCITATION OF SPECTRA.

We have discussed cosmical spectra so far chiefly from the point of view of the spectroscopist. It will now be of interest to consider the probable mode of excitation of some of them.

Let us consider first the polar aurora; this, as is well known, is closely bound up with exceptional conditions of magnetic disturbance, and these in turn are conditioned by solar influence. As regards the nature of this influence, the theory of Birkeland, elaborated by Störmer, still holds the field. The sun is regarded by them as emitting localised streams of electrically charged particles from limited areas of its surface.

This theory in its original simplicity has required a good deal of patching, and it is difficult to feel much satisfaction with the special *ad hoc* hypotheses which have had to be introduced into it. A stream of particles with a charge of one sign only is open to the criticism that the stream will dissipate itself by electrostatic repulsion, and loses the hard outline which is one of the most essential features. Lindemann has proposed to get over the difficulty by making the stream neutral on the whole, still consisting, however, of charged particles of both signs. Here, however, we lose too much of the magnetic flexibility of the stream. Chapman proposes

(Continued on p. 199.)

to retain a slight excess of charge of one sign, and in this way is able to arrive at a tolerable compromise.

The search for direct evidence might not seem at first sight very hopeful, but not long ago a sensational suggestion was made by Störmer. His attention was directed by Hals to echoes heard after short-wave (131 metres) wireless signals sent out from Eindhoven in Holland. These echoes have been found by Störmer and Hals at long intervals up to as much as fifteen seconds after the original reception. Now, if we bear in mind that with the velocity of light the longest terrestrial distances only give intervals about $\frac{1}{3}$ sec., it seems inevitable that some extra-terrestrial reflector should be looked for. Störmer finds this in the corpuscular stream as bent round by the earth's magnetic force. Though the boldness of the idea is staggering, it is difficult to suggest any alternative view.

T. L. Eckersley has made an observation on electrical disturbances of natural origin which he interprets as analogous to Störmer's. A click is heard in a telephone attached to a large aerial, which is followed at an interval of about three seconds by a 'whistler' or musical note of short duration. Further whistles follow at intervals of 3·8 sec., each more drawn out than the previous one. The musical notes are regarded as due to the spreading action of a dispersive medium on an electrical impulse. It is only at times of magnetic storm that these phenomena are frequent. Further development of observations of this kind will be awaited with keen interest.

To return to the nebular spectrum: although the main problem has been cleared up in the way described, it would still be an important step to imitate the spectrum in the laboratory, not so much to confirm the origin of the lines as to get direct information about the conditions under which they may be excited. A large volume and high rarefaction (rarity of collisions) is suggested by the nebular conditions, and was plausibly held by Bowen to be an essential. It must be allowed, however, that such experimental evidence as we have at present on passage downwards from metastable states does not definitely point in this direction.

METASTABLE STATES.

In discussing the nebular and auroral spectra, we encountered the idea of 'metastable states'. At present this conception is not in a very satisfactory condition. The original idea was of a state which did not allow of direct transition by emission of radiation to the stable ordinary state. Let us compare the levels of the atom to the stories of a building and the optical electron to a man inside the building. The ordinary state of the atom is represented by the man being on the ground floor, and the metastable state by placing him on the first floor. But the internal architecture of our building must be pictured as peculiar. A staircase connects the first floor with the second floor, and another staircase connects the second floor with the

ground floor: but there is no connexion between the first floor and the ground floor except by going up higher and coming down again.

Facts which have since come to light require some revision of this. In the nebulae the electron manages somehow to escape from its prison-house and descend to the level below, not by the legitimate route of going upstairs and down again, but by illicitly breaking through the floor. Abandoning the metaphor, the selection rule which forbids transitions not involving a change in the azimuthal quantum number is violated in all such cases. The inner quantum number rule, which requires that the inner quantum number should not change from 2 to 0 or from 0 to 0 is also violated in one class of cases, and rather meticulously observed in another. This rule permits only the pair of green nebular lines in doubly ionised oxygen which we have discussed; and in deference to it only two are observed, instead of the three which apart from this might have been expected from the triplet ground state. Yet we find the blue singlet line $\lambda 4363$ of this ion violating the same rule, and the same applies to the analogous case of the aurora line.

In the case of the mercury spectrum, which lends itself well to experimental observation and of which much detail is known, we have laboratory examples of the violation of this rule, as originally shown by experiments of Takamine, Fukuda, and other Japanese physicists. The lines were originally obtained under conditions where a strong electric field was acting, and this was sometimes urged in mitigation for breaking the rule. Again, the lines were of low intensity, and this too was thought to be a partial excuse.

Whatever might have been thought of these apologies originally, their irrelevance was, I think, clearly shown in some experiments of my own, in which one of the 'forbidden' mercury lines was obtained as the second strongest line in the entire mercury emission spectrum, in the vapour passing through a discharge, but altogether away from the region in which the discharge itself was taking place, and consequently in the absence of an extraneous electric field.

In another experiment I was able to obtain the other forbidden line as an absorption line in unexcited mercury vapour, and thus apparently in the absence of any disturbing conditions. In this experiment the quantity of vapour used was very large, about ten million times the amount required to bring out the resonance line of mercury in absorption. The probability of the transition thus indicated is very low, and for the other forbidden line it is apparently still lower. But for all that, as we have seen, this forbidden line can be got in considerable intensity in emission.

The necessary condition in the mercury experiments appears to be a large accumulation of mercury atoms in the relevant metastable state, so that, even with a low probability of transition for the individual excited atom, a considerable number of transitions occur. It has even been proposed to define a metastable state as one with a low probability of transition. This takes us far from the

original conception, and makes 'metastability' merely a question of degree. If this conclusion is accepted, a far-reaching revision of our present notions may become necessary. The general softening of outline on our picture of atomic events resulting from the substitution of wave groups for particles seems likely to afford what is required, and allow the occasional transition downwards from a metastable state.

UNKNOWN ELEMENTS OF HIGH ATOMIC WEIGHT.

Although we are no longer at liberty to postulate unknown light elements, we are free up to the present to postulate heavier ones than any known terrestrially. Jeans, as is well known, has made use of this hypothesis to explain the origin of stellar energy. In common with other authorities, he provides it by the destruction of matter, with radiation of the equivalent quantity of energy (mc^2) demanded by the theory of relativity. So far there seems to be fairly general agreement. The difficulties arise when we come to the question of stability, and here agreement is not general. Jeans considers that the source must liberate energy at a rate independent of the temperature. I am not qualified, and shall not attempt, to discuss this point. The object of postulating unknown heavy elements is to endow them with the property of going out of existence spontaneously at a rate which is independent of external conditions, except in so far as ionisation, which involves the removal of some of the electrons from the neighbourhood of protons, tends to hinder the process.

In the known radioactive elements we have, of course, instances of unstable forms of matter, and Jeans regards these as transitional; but it must be admitted that substances which undergo spontaneous disintegration do not at first sight form an altogether satisfactory half-way house between those which are quite stable on one side and those which spontaneously go out of existence on the other. Then we have to explain why these heavy atoms are not found on the earth, which, it is generally agreed, originally formed part of the same mass as the sun. Jeans mentions this difficulty, and gives reasons for thinking that the heavy elements would sink to the interior of the mass, so that the earth, formed from the exterior part of it, would not contain them. That a *vera causa* is here appealed to cannot be doubted; but there seem to be some difficulties in assuming that it operates with enough precision to secure the desired result.

The list of known elements ends with uranium, and we must notice that of the occupants of the 92 places in the list up to and including uranium, nearly all answer to their proper numbers when the roll is called. The only exceptions are 85 and 87; and he would be a rash philosopher who attached much importance to these vacant places, which may be filled up any day. Roughly speaking, we may say that the elements up to uranium are all present, and the higher members assumed to exist in the stars are all absent. It is putting a heavy burden on the mechanism of gravitational separation to expect it to achieve this result. The

inventors of ore-dressing machinery would, I should imagine, despair of accomplishing anything like it.

Nature works on a vast scale and with plenty of time at her disposal, and it may well be urged that we must be careful of measuring her possible achievements by our own. We may ask, however, whether the more direct indications available suggest that she has in fact made this separation. If there is this cut between the atomic numbers 92 and 93, we should expect most of 92 to have gone into limbo in order to ensure the *whole* of 93 having done so. Yet 92 (uranium) is a relatively abundant element compared with most, being in fact No. 25 on the list of abundance in igneous rocks. Again, we happen to be in a position to say that, on the earth at least, uranium, so far from having sunk to the centre, is concentrated near the surface.

Assuming that uranium exists on the sun as on the earth, then, as first pointed out by Lindemann, there are strong grounds for thinking that it must be in course of formation there, for the life of uranium is too short in comparison with the probable age of the sun to allow us to suppose otherwise. Those who remember the early development of radioactivity will recall that a parallel argument was successfully used by Rutherford to prove that radium must have originated on the earth before the fact was directly proved that it is being generated here. Radium (it was later shown) is generated from a parent body of higher atomic weight, namely, uranium. Jeans would regard the origin of uranium itself as analogous, and if this analogy is accepted it would require the presence of an element of still higher atomic weight, capable of undergoing radioactive disintegration, but, it is to be observed, incapable, *ex hypothesi*, of dissolving entirely into radiation.

No doubt these are very deep waters, and we can scarcely expect at present to fathom them. What would really be most helpful would be a theory of atomic structure in sufficiently definite agreement with experiment as regards known elements to enable us to proceed to investigate the properties of elements of higher number than 92 with confidence.

On the general question of whether the evolution of elements has proceeded from the simple to the complex, or from the complex to the simple, it does not seem to me very much to the purpose to appeal to evolutionary doctrine and the analogy of organic evolution, in favour of the former alternative. Is it not more to the point that radioactive changes are of the latter class? At present this is a question of scientific taste. Perhaps it is not irrelevant to remark that even in organic evolution degeneration of organisms sometimes occurs, and I do not know whether our biological colleagues are in a position to assert that the whole course of organic evolution may not at some future time be reversed by a change of conditions. At all events, it is something to have formulated the more restricted question of whether uranium now comes into being on the sun by a synthetic or an analytic process. It would seem that this is a well-framed question, and that the answer can scarcely be either *both* or *neither*.