ART. XLIII.—*The Chemical and Geological Relations of the Atmosphere* ;* by T. STERRY HUNT, LL.D., F.R.S.

QUESTIONS concerning the condition of the terrestrial atmosphere in former periods of the earth's history, and its geological relations, have occupied the attention of naturalists, physicists and chemists. Brongniart long since suggested that the abundant vegetation of the Coal-period indicated the existence of a large proportion of carbonic acid in the air at that time. Ebelmen, however, appears to have been the first to clearly understand the great geological significance of the atmosphere, and in his two remarkable memoirs on the decomposition of rocks, published in the *Annales des Mines* in 1845 and 1847,† treated the subject in its atmospheric relations with much research and philosophic breadth. Starting from the chemical changes of crystalline-silicate rocks, he considered both the conversion of feldspars into kaolin, and the decay of protoxide-silicates, such as amphibole and olivine. The sub-aerial decomposition of the feldspars had already been shown by Berthier to result in the separation, in a soluble form, of the protoxide-bases, together with a portion of silica, from an insoluble aluminous silicate of definite composition. The analyses of Ebelmen now established the fact that the protoxide-silicates just mentioned, lose, under similar conditions, the whole of their lime and magnesia, and nearly the whole of their silica, leaving little behind save the higher oxides resulting from the fixation of atmospheric oxygen by the ferrous and manganous oxides of the silicates ;

* A summary of the views presented in this memoir was given at Dublin, in August, 1878, before the British Association for the Advancement of Science. An abstract thereof appeared in the *Proceedings*, and will be found in *Nature* for August 29, 1878 (vol. xviii, p. 475.) The principal conclusions of the memoir are also embodied in a communication made by the author to the French Academy of Sciences, and published in the *Comptes Rendus* of September 23, 1878 (vol. lxxxvii, page 452.) They will also be found set forth in the preface to a second edition of the writer's *Chemical and Geological Essays* (pages ix-xix) published in the spring of the same year.

† 4th Series, vols. vii and xiii. These memoirs will also be found in the *Recueil des Trav. Scient. de M. Ebelmen* ; Paris, 1855, vol. ii, pp. 1-79.

the soluble bases being in all cases removed by atmospheric waters in the form of carbonates. Such a decomposition of these silicates shows that the removal of silica in soluble form does not depend on the intervention of alkalies.

The atmosphere of our earth at a pressure of 760 millimeters has a weight of 10,333 kilograms to the square meter, of which the oxygen equals 2,376, and the carbonic dioxide (if we take Boussingault and Léwy's determination of four and a half parts in 10,000 parts by weight) 4.64* kilograms. The alkali of 100 parts of orthoclase would require for its neutralization 7.8 parts of carbonic dioxide, so that a cubic meter of this silicate, of specific gravity, 2.5, would, by the calculation of Ebelmen, fix, in the process of decay, 195 kilograms of the gas. From this it results that a layer of orthoclase over the earth of 0.0238 meter, or one of less than 1.0 meter over one-fortieth of its surface, would, in its decomposition, absorb the whole amount of this gas now present in the atmosphere. Ebelmen further calculated that the formation of a layer of kaolin by this process, 500 meters in thickness, would require an amount of carbonic dioxide equal to many times the weight of the present atmosphere.

We have repeated and extended these calculations, with revised equivalent weights, and with the following results: A cubic meter of orthoclase, with a density of 2.5, and containing theoretically 16.9 per cent. of potash, equivalent to 7.89 of carbonic dioxide, would absorb in kaolinization 197.3 kilograms of this gas, while a cubic meter of albite of density 2.6, containing 11.8 of soda, equivalent to 8.37 of carbonic dioxide, would require not less than 217.6 kilograms of the same. The figure of 195 kilograms, adopted by Ebelmen, was thus below the truth, and we may, in view of the considerable proportion of soda-feldspar in the oldest crystalline rocks, conveniently assume 200 kilograms as the amount of carbonic dioxide required to unite with the alkali from a cubic metre of orthoclase or albite, and form therewith a neutral carbonate.

In such a decomposition, 100 parts of orthoclase give theoretically about 46.5 parts of kaolin, so that 1.0 meter in thickness of orthoclase of the above density should yield 0.447 meter of kaolin of density 2.6. If we assume this process to have consumed for a cubic meter or 2500 kilograms of orthoclase, 200 of carbonic dioxide, we find that a layer of 51.66 meters of orthoclase, or its equivalent of quartzo-feldspathic rock, in undergoing the same change, would absorb 10,333 kilograms of this gas, equal to the entire weight of the present atmospheric column, and would yield a layer of pure kaolin 23.7 meters in thickness. The production of a stratum of

* This, by an error in Ebelmen's memoir, is given as only 1.24 kilograms.

kaolin 500 meters in thickness over the whole surface of the globe, would thus require an amount of carbonic dioxide equal to more than twenty-one times the entire weight of our present atmosphere.

The absorption of this gas in the decay of silicates like hornblende, pyroxene and olivine is far greater. If we assume for convenience a hornblende containing 20·0 per cent of magnesia, and 14·0 of lime, with a density of 3·0 (which figures are not above the average) we find that it will require 33·0 per cent, or in round numbers one-third its weight of carbonic dioxide to convert these two bases into neutral carbonates; so that a meter-cube of hornblende, weighing 3000 kilograms, would consume not less than 1000 kilograms of carbonic dioxide. In other terms, the decay of $10\frac{1}{3}$ meters of such hornblende (or its equivalent in hornblendic rock) would absorb 10,333 kilograms, or a whole atmosphere of this gas, being five times as much as is taken up in the kaolinization of the same volume of orthoclase.

The hornblendes in question are seldom without several hundredths of iron as ferrous oxide, which is peroxidized in the process of decay, and, with a little silica, is the chief insoluble residue in the case of non-aluminous hornblendes. In this connection we revert to a farther calculation by Ebelmen, who pointed out that the conversion of 21,357 kilograms of ferrous oxide into 23,750 kilograms of ferric oxide would consume the whole of the 2,373 kilograms of oxygen contained in the present atmosphere; so that if we suppose the existence over the whole earth of 1,000 meters of sediments derived from the decay of crystalline rocks, and containing only one per cent of ferric oxide thus formed, this amount would equal 25,000 kilograms per square meter of surface, requiring for its production from ferrous oxide the absorption of a quantity of oxygen more than equal to that now contained in our atmosphere.

Ebelmen, at the same time, referred to the well-known deoxidation of carbonic dioxide by growing vegetation, and also to the reduction, by decaying organic matters, of sulphates to sulphids, with reproduction of carbonic dioxide, through which the generation of metallic sulphids in nature gives to the atmosphere, in union with carbon, a portion of the oxygen previously combined with sulphur and with the metals.

The following calculations may serve to bring still more fully before us the great geological significance of these atmospheric changes. The weight of a layer of pure carbon, with a density of 1·25 and a thickness of 0·7 meter, would require for its conversion into carbonic dioxide the whole of the oxygen of our present atmosphere. The separation of such an amount

of carbon by the process of vegetable growth must therefore have liberated the same volume of oxygen. Again, a stratum of carbonate of lime of specific gravity 2·7, covering the earth with a thickness of 8·69 metres, (or one of dolomite of sp. gr. 2·85, and 7·58 meters thick) would contain an amount of carbonic dioxide equal in weight to the present atmosphere.*

It was in view of these processes that Ebelmen declared, in 1845, that "the decomposition and the reproduction of certain mineral species very abundant on the surface of the globe corresponds to important modifications in the composition of the atmosphere." He farther said, "Many circumstances tend to prove that in ancient geological periods the atmosphere was denser, and more rich in carbonic acid, and perhaps in oxygen, than at present. To a greater weight of the atmospheric envelop would correspond a stronger condensation of the solar heat, and atmospheric phenomena of a much greater intensity."† Similar conclusions with regard to the physical relations of a denser primeval atmosphere were subsequently announced by the late Edwin B. Hunt, in an essay on *Terrestrial Thermotics*, presented to the American Association for the Advancement of Science, in 1849, and published in its *Proceedings* for that year, page 135.

We may get a clearer notion of the problem before us by inquiring into the probable amounts of carbonic dioxide which have, in past ages, been abstracted from the atmosphere. In a communication to the British Association for the Advancement of Science, in 1877,‡ Mr. J. L. Mott concludes, as the result of calculations, that the average amount of unoxidized carbon to a square mile of the earth's crust cannot be less, and is probably many times greater than 3,000,000 tons; while a layer of 0·7 meters of carbon of density 1·25, (about that of coal) which we have calculated to be equal to the total atmospheric oxygen, would weigh only about 2,200,000 tons to the square mile. Mr. Mott rightly argues that the presence in the atmosphere of so great an amount of carbon in the form of dioxide would imply a condition of things incompatible with the existence of animal life, and at the same time concludes that its deoxidation would yield an excessive amount of oxygen. He is hence led to assume the existence in the earth of a constant amount of carbon, which is subject to an annual subterranean oxidation equal to the amount of carbon annually removed by vegetation; the source of the original amount of carbon being, in his hypothesis, left unexplained.

* T. Sterry Hunt on the Primeval Atmosphere, *Proc. Amer. Assoc. Adv. Science*, 1866, and *Can. Naturalist*, II, iii, 118.

† *Ann. des Mines*, IV, vii, 65; also *Receuil des Trav. Scient. de M. Ebelmen*, vol. ii, p. 55.

‡ *Nature*, vol. xvi, p. 406.

While some have imagined an inorganic origin to the carbon found in the form of graphite, and even to petroleum and to coal, sound reasoning is, we think, on the side of those who, starting from the conception of an originally oxidized globe, see no evidence of any process of deoxidation therein which does not, directly or indirectly, depend upon vegetable life, and hence assign an organic origin to all carbons and hydro-carbons. When we take into account the vast amounts of these, from the graphite of Eozoic times to the coals, lignites and petroleums of the Tertiary, we can scarcely doubt that the total amount of carbon which has been reduced from carbonic dioxide is equal to many times the equivalent of the oxygen now present in the atmosphere. Whether the great excess of oxygen thus liberated may perhaps have been absorbed in the production of ferric oxide, as above indicated, is a part of the problem before us.

It may here be noted that in addition to the fossil carbonaceous bodies already mentioned, the rocky strata of the earth include great thicknesses of pyroschists, which are argillaceous sediments more or less impregnated with hydro-carbonaceous matters allied to coal in composition. To give a single example, Newberry estimates the proportion of such matters diffused through the 300 or 400 feet of Devonian black shales which underlie the eastern half of Ohio, to equal fifteen per cent, and to be equivalent to a layer of coal fifty feet in thickness over the whole area.*

In this connection it must be considered that the chemical composition of the various hydrocarbonaceous fossil substances implies a deoxidation not only of carbonic dioxide but of water. The amount of liberated oxygen from the latter would equal, for the different coals and asphalts, from one-eighth to one-fourth, and for the petroleums, one-half of that set free in the deoxidation of the carbon which these hydrocarbonaceous bodies contain.

The amount of carbon removed from the atmosphere in a deoxidized form by vegetation is, however, small when compared with that which has been absorbed during the decomposition of silicates, and is now fixed as insoluble carbonates, chiefly in the form of limestones and dolomites. That both the alkaline carbonates liberated in the decay of feldspars, and the magnesian carbonate set free in like manner from magnesian silicates, must decompose the chlorid of calcium contained in the primitive ocean, thereby giving rise to alkaline and magnesian chlorides on the one hand, and to carbonate of lime on the other, is a consequence which seems to have escaped Ebelmen, and was pointed out by the present

* *Geology of Ohio*, vol. i, page 162.

writer in 1858. In 1862, however, there was opened a sealed packet which had been in 1844 deposited by Cordier with the French Academy of Sciences, and was found to contain views as to the origin of limestones and of sea-salt similar to those just stated.* Thus, in the present state of our knowledge we conclude that all carbonates of lime, whether directly formed by the decay of calcareous silicates, or indirectly through the intervention of carbonates of magnesia or alkalies, derive their carbonic dioxide from the atmosphere. The same must be said for the dolomites, magnesites and siderites.

We have already shown that a weight of carbonic dioxide equal to more than twenty-one times that of our present atmosphere would be absorbed in the production from orthoclase of a layer of kaolin extending over the earth's surface with a thickness of 500 meters, an amount which evidently represents but a small proportion of the results of feldspathic decay in the sedimentary strata of the globe. The aluminous silicates in the oldest crystalline rocks occur in the forms of feldspars and related species, and are, so to speak, saturated with alkalies or with lime. It is only in more recent formations, that we find aluminous silicates either free or with reduced amounts of alkali, as in the argillites and clays, in micaceous minerals like muscovite, margarodite, damourite and pyrophyllite, and in kyanite, fibrolite and andalusite, all of which we regard as derived indirectly from the more ancient feldspars.†

It has been shown that the disengagement of the carbonic dioxide from a layer of limestone covering the earth's surface with a thickness of 8.69 meters, would double the weight of the atmosphere. The existence of vast formations of limestone and dolomite, often many hundred meters in thickness, throughout all geological periods, will, it is believed, justify the conclusion that the carbonates of the earth's crust are equal to a continuous layer of limestone 869 meters thick, and probably to more than double this amount. From this it would follow that the earth contains, fixed in the form of carbonates, a quantity of carbonic dioxide, which, if liberated in a gaseous form, would be equal in weight to one hundred if not to two hundred atmospheres like the present. A considerable portion

* Hunt, *Chem. and Geol. Essays*, pp. 2 and 20.

† These considerations, and their stratigraphical bearings, first set forth in 1863 (*Chem. and Geol. Essays*, pp. 27 and 28), will be found further developed in the writer's report on *Azoic Rocks*, 2d *Geol. Survey of Penn.*, 1878, p. 210. It is a question how far the origin of the various crystalline aluminous silicates named above is to be sought in a process of diagenesis in ordinary aqueous sediments holding the ruins of more or less completely decayed feldspars. Other aluminous rock-forming silicates, such as chlorites and magnesian micas, are however connected, through aluminiferous amphiboles, with the non-aluminous magnesian silicates, and to all these various magnesian minerals, as maintained in a previous paper in this volume (*History of some pre-Cambrian Rocks*, etc., page 270), a very different origin must be assigned.

of this was doubtless absorbed at an early period in the history of our globe, since the limestones of the Eozoic are of great thickness, and those of more recent times have been in part formed by the solution and re-deposition of portions of these older limestones.

The question now arises, whence came this enormous volume of carbonic dioxide which, since the dawn of life on our planet, has been fixed in the form of carbon and carbonates? The presence of even a small proportion of it at any one time in the terrestrial atmosphere is evidently incompatible with the existence of vegetable and animal life, and it may be added that the pressure of a column of this gas less than the minimum of 100 atmospheres which we have supposed, would suffice, at ordinary temperatures, for its partial liquefaction; the tension of liquid carbonic dioxide at $30^{\circ}\cdot7$ C. being, according to Mareska and Donny, but eighty atmospheres. We are therefore forced to the conclusion that this gas was gradually supplied from a source either within the earth or beyond our atmosphere.

The difficulties of this problem were not overlooked by Ebelmen, though he apparently failed to recognize their full weight. He takes care to remark: "I do not pretend that this immense proportion of carbonic acid ever made part, at any one time, of the terrestrial atmosphere. . . . I see in volcanic phenomena the principal agent which restores to the atmosphere the carbonic acid which the decomposition of rocks removes from it." He then inquires whether the carbonic acid (carbonic dioxide) evolved from the earth's interior, comes from the decomposition of carbonates at great depths and high temperatures by reactions with silicious matters, or whether we may imagine, with Elie de Beaumont, the existence of an immense reservoir of carbonic acid dissolved in the supposed liquid interior of the earth as oxygen is held in fused litharge or in molten silver. In either case, remarks Ebelmen, the cessation of volcanic phenomena would be followed by the removal from the atmosphere of the last traces of carbonic acid, a process which would entail the extinction of all vegetable and animal life.

Of these two suggested sources of the terrestrial carbonic dioxide, a little reflection will show that although the first is doubtless a true one, and will serve to account for that which is so often disengaged from the earth, both in volcanic and non-volcanic regions (having a similar origin to the chlorhydric, sulphuric and boric acids evolved under analogous conditions—namely, the decomposition of saline compounds of aqueous origin),* it by no means meets the requirements of the problem.

* Hunt, *Chem. and Geol. Essays*, pp. 8 and 111.

As preceding calculations have shown, it is not a question of a small amount of carbonic dioxide alternately removed from our atmosphere by sub-aerial reactions and restored to it by subterranean processes, but of a vast quantity of this gas which, at one time or another, has existed in the terrestrial atmosphere, but is now removed from the aerial circulation and locked up in the form of carbonates.

As regards the second source of carbonic dioxide, suggested by Ebelmen after Elie de Beaumont, it is, unlike the last, purely hypothetical. That the globe has a molten interior is, in the present state of our knowledge of terrestrial physics, very improbable, and if such exists, the notion that it intervenes directly in volcanic phenomena is still more so. The suggestion that such a molten interior might hold dissolved a great volume of carbonic dioxide appears, moreover, to be inconsistent with what we know of the behavior of furnace-slugs, which, though formed in atmospheres highly charged with this gas, do not, as shown by their behavior in cooling, hold it in solution. The tendencies of modern geological thought and investigation, it may be said, lead to the conclusion that the seat of volcanic phenomena is to be found in sedimentary strata,* and that although the earth's interior intervenes as a source of heat, the carbonic dioxide disengaged from its crust is derived, as in the first hypothesis mentioned by Ebelmen, from the decomposition of carbonates previously generated by sub-aerial reactions.

The problem still before us is then to find the source of the vast amount of carbonic dioxide continuously supplied to the atmosphere throughout the geologic ages, and as continuously removed therefrom, and fixed in the form of carbonaceous matters and limestones. We have shown reasons for rejecting the theory which would derive this supply either from the earth's interior or from its own primal atmosphere, and must therefore look for it to an extra-terrestrial source. The new hypothesis, which we here advance, starts with the assumption that our atmosphere is not primarily terrestrial but cosmical, and that the air, together with the water surrounding our earth, (whether in a liquid or a vaporous state) belongs to a continuous elastic medium which, extending throughout the interstellar spaces, is condensed around attracting bodies in amounts proportional to their mass and temperature. This universal atmosphere (if the expression may be permitted,) would then exist in its most attenuated form in the regions farthest distant from these centers of attraction; while any change in the gaseous envelope of any globe, whether by the absorption or condensation, or by the disengagement of any gas or vapor

* *Ibid*, pp. 59-67.

would, by the laws of diffusion and static equilibrium, be felt everywhere throughout the universe.

The precipitation of water at the surface of a cooling globe, and its chemical or mechanical fixation there, would thus diminish the proportion of gaseous water throughout all space. The oxygen liberated in the growth of terrestrial vegetation would be shared with the remotest spheres, while the condensation of carbonic dioxide at the surface of our own or any other planet, would not only bring in a supply of this gas from the atmospheres of other bodies, but by reducing the total amount of it, would diminish, *pro tanto*, the barometric pressure at the surface of this and of all other worlds.

The hypothesis here advanced is not wholly new. Sir William R. Grove, in 1842, suggested that the medium of light and heat may be "a universally diffused matter," and subsequently, in 1843, in his celebrated Essay on the Correlation of Physical Forces, in the chapter on Light, concludes, with regard to the atmospheres of the sun and planets, that there is no reason why these atmospheres "should not be, with reference to each other, in a state of equilibrium. Ether, which term we may apply to the highly attenuated matter existing in the interplanetary spaces, being an expansion of some or all of these atmospheres, or of the more volatile portions of them, would thus furnish matter for the transmission of the modes of motion which we call light, heat, etc., and *possibly minute portions of these atmospheres may, by gradual accretions and subtractions, pass from planet to planet, forming a link of material communication between the distant monads of the universe.*" Subsequently, in his address as President of the British Association for the Advancement of Science, in 1866, Grove further suggested that this diffused matter might become a source of solar heat, inasmuch as the sun "may condense gaseous matter as it travels in space, and so heat may be produced."

This bold speculation of a universally diffused matter, constituting an interstellar medium, though thus repeatedly insisted upon by Grove, has passed almost unnoticed. It seems to have been unknown to Mr. W. Mattieu Williams, who in 1870 published his very ingenious work entitled "The Fuel of the Sun,"* which is based on a similar conception, without citing in support of it the high authority of Grove. The solar heat, according to Williams, is maintained by the sun's condensation of the attenuated matter everywhere encountered by that body in its motion through interstellar space. The irregular movements impressed upon the sun by the varying attractions of the planets, stirring up and intermingling the

* See also Williams on The Radiometer and its Lessons, Quart. Jour. Science, Oct., 1876.

different strata of the solar atmosphere, and producing the great perturbations therein of which the telescope affords evidence—are, in his hypothesis, the efficient agents in this process. The diffused matter or ether, which is the recipient of the heat-radiations of the universe, is thereby drawn into the depths of the solar mass; expelling thence the previously condensed and thermally-exhausted ether, it becomes compressed, and gives up its heat, to be, in turn, itself driven out in a rarified and cooled state, and to absorb a fresh supply of heat, which he supposes to be in this way taken up by the ether, and again concentrated and redistributed by the suns of the universe. (Loc. cit., chap. v.)

Neither Grove nor Williams has considered the hypothesis of an interstellar medium in its geological relations. Dr. P. Martin Duncan, however, in his address as President of the Geological Society of London, in May, 1877, without noticing the priority of Grove, has adopted it from Williams,* but instead of supposing, with these, that the atmospheres of all bodies are in equilibrium, conceives the sun, in virtue of its greater mass, to be slowly attracting to itself the earth's terrestrial envelope. He thence proceeds to deduce therefrom important geological considerations, maintaining that from the greater height of the terrestrial atmosphere which, according to this view, must have prevailed in former ages, there would have resulted a higher temperature at the earth's surface, more aqueous vapor, and a more equable climate. From a more abundant precipitation would also follow greater sub-aerial denudation, while the formation of ice, though it might occur in elevated regions, would be impossible at or near the sea-level.

The correctness of all these deductions by Duncan from the condition of a denser terrestrial atmosphere appears to be indisputable, and, as we shall endeavor to show in the sequel, they are in harmony with the geological record. But, while admitting that changes in the earth's atmosphere conducing to such results have taken place, we maintain, in accordance with the principles already laid down, that these changes have not been due to solar attraction and absorption, but to the chemical and mechanical processes going on at the surface of the earth and other bodies in space, whereby the atmospheric elements are condensed in the forms of liquid and solid water, or fixed as hydrates, oxides, carbonates and hydrocarbonaceous matters.

The changes which have thus been produced in the terrestrial atmosphere are, by our hypothesis, reduced in amount by being shared with other worlds, and the consequences which

* It is due to my friends, Mr. Williams and Dr. Duncan, to say that they have both, in conversation, informed me that they were ignorant of the priority of Sir William Grove. The conception appears to have been original and independent in the mind of Mr. Williams.

Ebelmen, and others after him, have deduced with regard to the temperature of the earth's surface in former geological periods, would seem, at first sight, to be invalidated. Tyndall, however, in 1861, from a consideration of the great power of absorbing heat possessed alike by aqueous vapor and by certain gases, such as carbonic dioxide, and the consequent effects of small quantities of these in the atmosphere on terrestrial radiation, and thus on climate, was led to remark, "it is not therefore necessary to assume alterations in the density and height of the atmosphere to account for different amounts of heat being preserved to the earth in different times: a slight change in its variable constituents may have produced all the mutations of climate which the researches of geologists reveal."* Thus, although the amount of carbonic dioxide which, in past geological ages, has been, by chemical processes at the surface of our own and other worlds, abstracted from the universal medium, may not have sufficed to diminish by more than a small fraction the barometric pressure at the earth's surface, this change would still meet all the requirements of geological history, so far as temperature and climate are concerned. From this point of view, the suggestion of Tyndall assumes a weight and a significance not hitherto suspected.

We have thus briefly endeavored to show how the hypothesis of a universal atmosphere serves to explain certain chemical and physical facts in the history of our globe. To discuss it in all its bearings would require a volume. The climatic influences of a denser terrestrial atmosphere, or one of greater absorptive power than the present, have been indicated by Ebelmen, E. B. Hunt and Duncan, and, as we have seen, the gradual changes in the composition of the atmosphere imply a slow progressive diminution of the mean annual temperature of the earth's surface. This conclusion is in contradiction with the hypothesis of secular oscillations of the earth's temperature, due to astronomical causes, and giving rise to successive periods characterized by general glaciation, and leads us to interrogate on this point the geological record. We may inquire (1) whether, since the appearance of terrestrial vegetation, the mean annual temperature of the earth has ever been less, and (2) whether it has ever been greater than at present. It is clear from paleontological evidence that a very warm climate prevailed over the arctic regions during the Carboniferous, Triassic, Jurassic, and Lower Cretaceous periods, and that the refrigeration apparent in the Upper Cretaceous gradually augmented up to the Pliocene, the cold of which has continued till now, subject to certain variations in its distribution which are

* Tyndall, Bakerian lecture for 1861; *L. E. & D. Phil. Mag.*, Oct., 1861, and Hunt, *Chem. and Geol. Essays*, pp. 42 and 46.

readily accounted for by changed geographical conditions. Such changes of sea and land are, however, inadequate to explain the elevated temperature which, according to the observations of Nordenskiöld, prevailed in the Carboniferous age, when the arctic climate permitted the development, over a great area of land, of a vegetation not unlike the Carboniferous flora of the inter-tropical regions. It is not easy to conceive that, with an atmosphere like that of the present time, any geographical conditions could maintain during the long polar winter the mild climate required for such a vegetation, even in insular regions, and still less over a continental area within the polar circle.

We are thus led to the conclusion that geographical changes, though adequate to explain the *greater refrigeration* of certain areas since the beginning of Pliocene time, are not sufficient to account for the *warmer climates* of previous ages, and to find the explanation of these in the different relations of the earlier atmosphere alike to solar and to terrestrial heat.

It is, however, obvious that, with such an atmosphere as we have supposed, the more elevated portions of the earth's surface might, as is now the case in inter-tropical lands, be lifted into regions where glaciation was possible, while a warm climate prevailed everywhere at the sea-level. Neither the glacial periods of more recent times, nor those of remoter geological ages, of which evidence is not wanting, necessarily depend upon any diminution in the earth's mean annual temperature at the sea-level. Glacial periods are, in this view, as has been well said by J. F. Campbell, not celestial, but local and terrestrial,* while, on the contrary, the warmer polar climates of Paleozoic and Mesozoic times are to be regarded as evidence of a generally elevated temperature at the earth's surface depending on atmospheric conditions, as already set forth.

In a note in the Comptes Rendus of the French Academy of Sciences, for Oct. 7, 1878, criticising my previous one of Sept. 23 "Sur les relations géologiques de l'atmosphère," already referred to at the beginning of this paper, Mr. Stanislas Meunier has argued in favor of the terrestrial origin of the atmospheric carbonic dioxide, the source of which he supposes to be a subterranean oxidation of a primitive store of carbon, a view which seems unsupported by any facts or analogies in nature. He opposes to the hypothesis which I have advocated, the fact of the absence of an atmosphere from the moon, while he asserts the existence of an abundant one around both Mercury and Venus. The evidences of such an atmosphere around the latter planet are well known, but the observations of recent

* Campbell on Glacial Periods; Quart. Jour. Geol. Soc., 1879, vol. xxxv, p. 98.

astronomers leave it doubtful, on the contrary, whether Mercury possesses a perceptible one, while, as regards our satellite, the conclusion, as stated by Newcomb, is that the lunar atmosphere, if it exist, is not equal to more than one four-hundredth that of the earth.

A little reflection will, however, show that the absence of any apparent atmosphere from the moon in no way militates against our hypothesis, since a completely refrigerated globe, such as our satellite must probably be, would long since have absorbed mechanically into its interstices, its share of the universal gaseous medium. It was many years since pointed out by Sæmann* that, as a consequence of the progressive refrigeration of our planet, the ocean and the air which surround it must one day disappear from its surface. The total volume of our atmosphere, at the density which it has at the sea-level, is, according to his calculation, less than four thousandths of that of the earth, the volume of the ocean being very much less. There is no known mass of cooled rock which has not a greater porosity than is represented by these figures, so that the conclusion seems inevitable that, with the complete refrigeration of the earth which must come in the course of ages, its atmosphere, following the ocean, will have so completely sunk into the pores of the cooled mass that its tension at the surface would be very small. Such a condition of things, Sæmann supposes to have been already attained in our satellite, a view which may be, with equal probability, extended to Mercury.

The hypothesis that interstellar space is filled with an attenuated matter which, in a more condensed form, constitutes the atmosphere and the waters of our own and other worlds, which we have already discussed in some of its chemical and geological bearings, assumes a new interest in connection with recent speculations as to evolution in the stellar universe. In considering the increasing chemical complexity revealed by the spectroscope in passing from nebulæ to white, yellow and red stars, Prof. F. W. Clarke, of Cincinnati, was led in 1873† to suggest the possibility of a generation of the higher from simpler forms of matter by a process of cosmical chemistry. A similar view was a few months later advanced by Mr. Lockyer, who reiterated and enforced these suggestions, showing that the chemical elements make their appearance in the cooling stars in the order of their vapor-densities—and moreover connected these considerations with the conjectures of Dumas as to the probably compound nature of the so-called

* Sur l'unité des phénomènes géologiques dans le système planétaire du soleil, *Bull. Soc. Géol. de Fr.*, 1860-61, vol. xviii, p. 322, translated by the present writer for this Journal, II, xxxiii, p. 36.

† *Popular Science Monthly*, Jan., 1873, vol. ii, p. 32.

elements.* Mr. Lockyer has since extended this inquiry by his ingenious and beautiful spectroscopic studies, the results of which are embodied in his "Discussion of the Working Hypothesis that the so-called Elements are Compound Bodies," communicated to the Royal Society, Dec. 12, 1878.† In his first note, of 1873 (which is embodied in the later paper) he suggested that we see in the stars evidences of a *celestial dissociation* under the influence of intense heat, which, continuing the work of our furnaces, would break up the metalloids, and leave only the metallic elements of low equivalent weight which are found in the hottest stars. In his later memoir he further suggests that as there may be no superior limit to temperature, so of dissociation there may be no end.

With these may be compared the views enunciated by the present writer in a lecture before the Royal Institution, May 31, 1867, wherein, discussing the problems of stellar chemistry, he declared that the "dissociation of elements by intense heat is a principle of universal application," and with regard to the chemical elements, that their "further dissociation in stellar or nebulous masses may give us evidence of matter still more elemental than that revealed by the experiments of the laboratory, where we can only conjecture the compound nature of many of the so-called elementary substances."‡ In 1874, while discussing the speculations of Dumas, Clarke and Lockyer, he further suggested that the green line in the spectrum of the solar corona, which had been supposed to indicate a hitherto unknown element, may be a "more elemental form of matter, which, though not seen in the nebulae, is liberated by the intense heat of the solar sphere, and may possibly correspond to the primary matter conjectured by Dumas, having an equivalent weight one-fourth that of hydrogen."§ Regarding this supposed element in the solar atmosphere, Prof. C. A. Young remarks that it must be of excessive tenuity, "a near relative, so far as gravity is concerned, to the luminiferous ether, and to the *Urstoff* of the German speculators."|| In this connection it should be mentioned that Hinrichs, in 1866, put forth an argument¶ in favor of the existence of such a primitive matter or *Urstoff* from a consideration of the wavelengths in the spectra of the various elements.**

* Comptes Rendus, Nov. 3, 1873.

† This Journal, III, xvii, 93-116; and farther, Clarke, Science News, Feb. 15, 1879, page 114.

‡ Reprinted from Proc. Royal Institution in Chem. and Geol. Essays, p. 37.

§ A Century's Progress in Theoretical Chemistry, by T. S. Hunt, being an address delivered on the Centennial of Chemistry, at Northumberland, Penn., July 31, 1874; Amer. Chemist, vol. v, pp. 46-51, and Pop. Science Monthly, vii, 420.

|| This Journal, II, xlii, 350-368.

¶ This Journal, III, i, 319.

** Since these pages were in type my attention has been called to a paper read before the Literary and Historical Society of Quebec in January, 1870, by James

Lavoisier long since suggested that hydrogen, nitrogen and oxygen are, with heat and light, the simpler forms of matter from which all others are derived, and when it is considered that the first two of these are the only elements of which we have yet any certain evidence in the nebulæ, it will be seen that the speculation of Lavoisier is really an anticipation of that view to which spectroscopic study has led the chemists of to-day. The three elements named by him are those which, in the forms of air and watery vapor, make up nine hundred and ninety-nine thousandths of the atmosphere which, in accordance with our hypothesis, constitutes the interstellar medium. It was in view of all these considerations that the writer in 1874 ventured to say that "the nebulæ and their resultant worlds may be evolved by a process of chemical condensation from this universal atmosphere; to which they would sustain a relation somewhat analogous to that of clouds and rain to the aqueous vapor around us."* Such a speculation, which seeks for a source of the nebulous matter itself, is perhaps a legitimate extension of the nebular hypothesis.

Montreal, Feb. 14, 1880.