OF ATMOSPHERES UPON PLANETS AND SATELLITES.[1]

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INTRODUCTION.

THE present writer began early in the sixties to investigate the phenomena of atmospheres by the kinetic theory of gas, and in 1867 communicated to the Royal Society a memoir,[2] which pointed out the conditions which limit the height to which an atmosphere will extend, and in which it was inferred that the gases of which an atmosphere consists attain elevations depending on the masses of their molecules, the lighter constituents overlapping the others. This was disputed at the time, on account of its supposed conflict with Dalton's law of the equal diffusion of gases;[3] but physical astronomers now recognize its truth.

On December 19, 1870, the author delivered a discourse before the Royal Dublin Society, which was the first of the series of communications, of which an account is given in the following pages. One of the topics of that discourse was the absence of atmosphere from the Moon. This was accounted for by the kinetic theory of gas; inasmuch as the potential of gravitation on the Moon is such that a free molecule moving in any outward direction with a velocity of 2.38 kilometers[4] per second

[1] Reprinted from an advance copy of a paper in the *Transactions of the Royal Dublin Society*, Vol. VI, Part 13. Communicated by the author.

[2] See an extract from this Memoir on p. 28, below.

[3] According to the Kinetic theory Dalton's Law will be true of mixtures of gases if the free paths of the molecules between their encounters are straight. This is the case, to an excessively close approximation, in all laboratory experiments; but the law ceases to hold at elevations in the atmosphere where the longer and more slowly pursued free paths are sensibly bent by gravity.

[4] It is very desirable that the names of metric measures should be made English words, and pronounced as such. Thus kilometer, hektometer, and dekameter should be pronounced with the accent on the second syllable, as in thermometer, barometer,

would escape, and, accordingly, the Moon is unable to retain any gas, the molecules of which can occasionally reach this speed at the highest temperature that prevails on the surface of the Moon.

Shortly after, a second communication was made to the Royal Dublin Society, at one of its evening scientific meetings, based on the supposition that the Moon would have had an atmosphere consisting of the same gases as those of the Earth's atmosphere, were it not for the drifting away of the molecules. It was shown that if the molecules of these gases can escape from the Moon, it necessarily follows that the Earth is incompetent to imprison free hydrogen ; and this was offered as explaining the fact that, though hydrogen is being supplied in small quantities to the Earth's atmosphere by submarine volcanoes and in other ways, it has not, even after the lapse of geological ages, accumulated in the atmosphere to any sensible extent. This communication was followed at intervals by others, in which the investigation was extended to other bodies in the solar system, in which an endeavor was made to trace what becomes of the molecules that filter away from these several bodies, and in which it was suggested that the gap in the series of terrestrial elements between hydrogen and lithium may be accounted for by the intermediate elements (except helium) having escaped from the Earth at a remote time, when the Earth was hot.

In one of the earlier of these communications, it was pointed out that it is probable that no water can remain on Mars — a probability which is now raised to a certainty by the recent discovery, that helium (with a molecular mass twice that of hydrogen) is being constantly supplied in small quantities to the Earth's atmosphere by hot springs, and probably in other ways, and that nevertheless there is no sensible accumulation of it in the Earth's atmosphere after the infiltration has been going on for cosmical ages of time. In the absence of water, carbon dioxide was sug-

etc. This would have the further useful effect of better distinguishing these names from decimeter, centimeter, and millimeter, which have accents on the first and third syllables.

gested as, with some probability, the substance that produces the polar snows upon Mars. Moreover, on the Earth, snow, rain, and cloud are produced by the lightest constituent of our atmosphere; but if the atmosphere of Mars consist of nitrogen and carbon dioxide, snow, frost, and fog on that planet are being produced by the heaviest constituent. An attempt was made to follow out the consequences of this state of things, and to refer to it those recurring appearances upon Mars which, though very imperfectly seen owing to the great distance from which we observe them, have been (perhaps too definitely) mapped and described under the name of canals.

Of this series of communications, though known to many, only imperfect printed accounts have appeared; and it is the object of the present communication to present the subject in a more complete form. The opportunity will be taken of substituting better numerical results for those originally given, by basing them on the fact which has recently come to our knowledge, that not only hydrogen, but helium also, with a density twice that of hydrogen, can escape from the Earth. The most notable change that this makes is, that what was before probable is now certain — that water cannot in any of its forms, be present upon Mars.

CHAPTER I.

Of the fundamental facts.—In order to see why neither hydrogen nor helium remains in the Earth's atmosphere, and why there is neither air nor water on the Moon, it is necessary to understand the conditions which determine the limit of an atmosphere. These were investigated under the kinetic theory of gas by the present writer in a memoir communicated to the Royal Society in May, 1867: see his paper "On the Physical Constitution of the Sun and Stars," in the *Proceedings of the Royal Society*, No. 105, 1868, from page 13 of which it will be convenient to make the following extract:[1]

[1] Further information on this subject will be found in sections 22, 24, 25, 26, and in the footnote to section 93, of the paper here quoted.

"23. Let us 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 influence while within the layer, and therefore pass out of it with altered direction and speed. Let us call them 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 besides 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 their 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 decrease will not be appreciably affected by molecules thus falling back. But in those regions where the atmosphere is both 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."

It appears, then, that the atmosphere round any planet or satellite will, *cæteris paribus*, range to a greater height the less gravity upon that body is; and that if the potential of gravitation be sufficiently low, and the speed with which the molecules dart about sufficiently great, individual molecules will stream away from that body, and become independent wanderers throughout space.

Thus, we shall presently see that, in the case of the Earth, a velocity of about eleven kilometers per second (nearly seven miles) would be enough to carry a molecule at the boundary of our atmosphere off into space, if the Earth were alone and at rest; and a somewhat less velocity of projection (about 10.5^{km} per second) is sufficient, on account of the rotation of the Earth, and because westerly winds sometimes blow in the upper regions of the atmosphere. The modification introduced by these subsidiary causes will be examined in Chapter IV, and the amount of their effect will be determined. The behavior of molecules is also slightly affected by the Moon, which is near enough sensibly to alter the orbits of molecules if shot up in some directions.

Let us now consider what would happen if free hydrogen could remain in our atmosphere. Hydrogen is, in modern times, being supplied in small quantities to the Earth's atmosphere by submarine[1] volcanoes and in other ways. Even if there were no tendency in hydrogen to leak away, it could not, in the free state become a *large* constituent of our atmosphere, because, when it came to be a certain proportion of the atmosphere, it would, on the occasion of the first thunderstorm or on account of fires, enter into combination with the oxygen, which is, in modern times, a large constituent of the atmosphere; but after each such explosion it would accumulate until it became a minor constituent like carbon dioxide were it not for the events described in this paper; and in former times, before there was vegetation to evolve free oxygen, it might have been a large constituent but for those events. The free hydrogen which con-

[1] The hydrogen evolved by terrestrial volcanoes burns into water on reaching the air, and ceases to be free hydrogen.

tinues in modern times to be supplied in small quantities to the atmosphere is used up in some way. A little may be occluded, some may suffer surface condensation, and the rest is escaping.

The evidence that there is an escape of gas from the Earth's atmosphere is still more conspicuous in the case of helium. Small quantities of this gas are constantly being dribbled into the atmosphere by hot springs and probably in other ways, and it was probably supplied more copiously in former times. Now helium is so little disposed to enter into combination with other elements, that the efforts of chemists to effect any such union have been unavailing. We must conclude, therefore, that this gas remains unchanged within the atmosphere, where it would therefore, in the lapse of time, have accumulated so as to be now a sensible and perhaps a large constituent of the Earth's atmosphere were it not that it is escaping from the atmosphere's outer boundary as rapidly as it enters it below—indeed so promptly escaping, that the amount *in transitu* is too small for the appliances of the chemist to detect it.

On the other hand, water is not sensibly leaving the Earth. From which we learn that the potential of the Earth and the temperature at the boundary of its atmosphere are such as enable our planet effectually to imprison the vapor of water with molecules whose mass compared with molecules of hydrogen is 9 (and probably ammonia with a density of 8.5.). The other constituents of the Earth's atmosphere, such as nitrogen, oxygen, and carbon dioxide, have still heavier molecules. Accordingly, none of these escape in sufficient numbers to produce any perceptible diminution of the quantity of gas upon the Earth.[1] We may infer from this that *the boundary between those gases that can effectually escape from the Earth and those which cannot, lies somewhere between gas consisting of molecules with twice the*

[1] We need not suppose that there is absolutely no escape of the molecules of the denser gases, but only that the event is an excessively rare one. Thus, if the molecules of a gas escape so very seldom that only a million succeed in leaving the entire atmosphere of the Earth in each second, then a simple computation will show that it would take rather more than 30 millions of years for a uno-twenty-one (the number represented by 1 with 21 ciphers after it) of these molecules to have escaped. Now a

mass of molecules of hydrogen and gas with molecules whose mass is nine times[1] *the mass of molecules of hydrogen.*

This we may take to be one fact which we can ascertain by observing what occurs upon the Earth, and the telescope has been able to reveal to us another fact of a like kind, viz., that there is either no atmosphere upon the Moon, or excessively little—a fact which has been made certain by the application of very delicate tests.

CHAPTER II.

Interpretation by the kinetic theory.—In order to make these facts the starting-point for fresh advances, we must study their precise physical meaning when interpreted by the kinetic theory of gas.

The velocity whose square is the mean of the squares of the velocities of the individual molecules of a gas—"the velocity of mean square" as it has been called—was determined[2] by Clausius to be

$$w = 485\sqrt{\frac{T}{273\,\sigma}} \text{ meters per second,}$$

where w is the velocity of mean square, T the absolute temperature of the gas measured in Centigrade degrees, and σ its specific gravity compared with air. We shall find it convenient to use ρ instead of σ, where ρ is the density of the gas compared with hydrogen. Accordingly $\sigma = \rho / 14.4$, whereby Clausius' formula becomes

uno-twenty-one is about the number of molecules which are present within every cubic centimeter of the gas at such temperatures and pressures as prevail at the bottom of our atmosphere. An escape of molecules of the denser constituents of the atmosphere on this excessively small scale, or even on a scale considerably larger, may be and probably is going on. See a paper on the "Internal Motions of Gases" in the *Philosophical Magazine* for August 1868, where the number of molecules in a gas is estimated. Readers of that paper are requested to correct a mistake at the end of the third paragraph, where 16^2 was by an oversight inserted instead of $\sqrt{16}$.

[1] We shall find in the chapter on Venus that the presence of water on that planet enables us to somewhat lower the upper of these two limits.

[2] *Phil. Mag.*, **14**, 124, 1857.

$$w = (111.4)\sqrt{\frac{T}{\rho}}, \qquad (1)$$

in meters per second. This formula gives a velocity of 1603 meters, nearly a mile a second as the "velocity of mean square" in hydrogen at an absolute temperature of 207°, *i. e.*, at a temperature which is 66° C. below freezing point. This is the "velocity of mean square" of the molecules of hydrogen in an atmosphere consisting either wholly or partly of hydrogen, at any situation in which the gas is at that low temperature. Similarly by putting $\rho = 2$ and $T = 207$, we find the velocity of mean square for helium at the same low temperature. It is about 1133 meters per second. The actual velocities of the molecules are, of course, some of them considerably more and others considerably less than this mean, even if the hydrogen or helium be unmixed with other gases; and the divergences of some of the individual velocities from the mean will become exaggerated when the encounters to which the molecules of these lighter gases are subjected are sometimes with molecules many times more massive, and which may, when the encounter takes place, be moving with more than their average speed, as must often happen in our atmosphere. Under these circumstances we should be prepared to find that a velocity several times the foregoing mean is not unfrequently reached; and the evidence (see Chapter IV) goes to show that *a velocity which is between nine and ten times the velocity of mean square*, a velocity which is able to carry molecules of either hydrogen or helium away from the Earth, *is sufficiently often attained to make the escape of gas effectual.*

We are now in a position to aim at making our results so definite that they may be extended to other bodies in the solar system.

CHAPTER III.

Dynamical equations.—In making our calculations with reference to the planets and satellites of the solar system, it will simplify the work, and be sufficient for our purpose, to treat them as spherical bodies, consisting of layers each of which is a spherical shell of uniform density. In that case, if B be one of these bodies

a (the acceleration of the surface of B, due to attraction)

$$=\frac{M}{R^2}, \tag{2}$$

and

$$K \text{ (the potential of gravitation at its surface) } = \frac{M}{R}, \tag{3}$$

where M is the mass of B, and R the radius of its spherical surface.

Now K, the potential, as we learn in the science of dynamics, expresses the kinetic energy stored up per unit of mass by a small[1] body in falling upon the surface of B from infinity. Hence,

$$K=\frac{v^2}{2}, \tag{4}$$

where v is the velocity which would be acquired by a small mass

[1] By a small body is to be understood one whose mass bears to the mass of B, a ratio so small that, from the physical standpoint, it may legitimately be regarded as a small quantity of at least the first order. For this purpose, a ratio of a tenthet, that is, of a unit in the tenth place of decimals, is sufficiently small in almost every branch of physical inquiry. If M be the mass of B, and m the mass of the body falling upon it, then the energy changed from potential into kinetic energy, by allowing them to fall together from infinity,

$$=\frac{m\,v^2}{2}+\frac{M\,V^2}{2},$$

if we suppose them to have started from rest, and if on coming together they have acquired the velocities V and $-v$. Now, by the principle of the center of mass, $MV+mv=0$. Therefore the acquired kinetic energy may be written

$$=\frac{m\,v^2}{2}\left[1+\left(\frac{m}{M}\right)\right],$$

which differs from being

$$=\frac{m\,v^2}{2}$$

by an insensible quantity if the ratio m/M is sufficiently small. And it is much more than sufficiently small from the physical standpoint, in the cases we are concerned with, where m is the mass of a gaseous molecule, and M the mass of a planet or satellite. In fact m is here of about the fifth order of small quantities compared with M, if we take a tenthet (10^{-10}) as about the ratio between quantities of two consecutive orders.

in falling from infinity. If a missile were projected from B with this speed, it would just be able to reach infinity, *i. e.*, this speed is the least which would enable a molecule to get completely away from B. We may, therefore, call it *the minimum speed of escape* from B when B is at rest. If B rotates, a less velocity relatively to the surface of B will suffice, provided that the missile is shot off in the direction towards which the station from which it starts was being carried by the rotation at the instant of projection.

CHAPTER IV.

Of the Earth.—Let us apply these elementary dynamical considerations to the Earth. In doing this, we may assume—

R (the Earth's equatorial radius), - -	= 6378 kilometers
h (the height of the atmosphere), - -	= 200 "
g (gravity at E, a station on the equator, at the bottom of the atmosphere), - -	= 978.1 ^{cm}./sec./sec.
u (the velocity at the equator due to the Earth's rotation), - - - -	= 464 ^{m}./sec.

We shall need one other datum, viz., the highest temperature which can be reached by the air at station E', where E' is a station at the top of the atmosphere, over the equator. To enable us to arrive at definite results, we shall regard this temperature as $-66°$ C. Our numerical results would be affected, but would only suffer a slight alteration, by substituting for this particular temperature any other which is admissible. It is, accordingly, legitimate to make our computation on this assumption, viz., that the temperature at station E' is $66°$ C. below freezing point. At this temperature Clausius' formula, equation (1) gives for the velocity of least square in a gas

$$w = (111 \cdot 4)\sqrt{\frac{207}{\rho}}, \\ = 1603 / \sqrt{\rho}, \qquad (5)$$

if we here use w to signify the velocity of least square at this particular temperature.

Let us next calculate a, the acceleration due to the attraction of the Earth at station E (on the equator, and at the bottom of the atmosphere). Here

$$a = g + \gamma, \tag{6}$$

where g is gravity at the equator, and γ the acceleration due to the Earth's rotation, *i. e.*,

$$\gamma = \frac{u^2}{R} = \frac{(464\ \text{II})^2}{6378\ \text{V}},$$
$$= 3.4^{\text{cm.}} / \text{sec.} / \text{sec.}, \tag{7}$$

where we use II for the two additional ciphers, and V for the five additional ciphers, which are necessary to express u and R in C. G. S. measure.[1]

Introducing this value of γ into equation (6), we find

$$a = g + \gamma = 978.1 + 3.4$$
$$= 981.5 \text{ cm.} / \text{sec.} / \text{sec.} \tag{8}$$

Again, $a = M / R^2$, where M, the mass of the earth, is expressed in gravitation units, and K' (the potential at station E', which is at the top of the atmosphere) $= M / (R + h)$. Taking the ratio of these we get rid of M, so that it is immaterial in what units it has been expressed. We thus find

$$K' = a\frac{R^2}{R+h} = (981.5)\frac{(6378\ \text{V})^2}{6578\ \text{V}},$$
$$= l^{-1}\ 11.7830, \tag{9}$$

where l^{-1} means "the number whose logarithm is." This result is expressed in C. G. S. measure.

Now $K' = v^2 / 2$ (see equation 4), where v' is the minimum speed of projection which would carry a molecule clear away from the Earth, if the Earth were stationary. We thus find

$$v' = 1101500 \text{ cm.} / \text{sec.},$$

[1] The author has found it very convenient, especially in investigations touching on molecular physics, to use Roman figures to represent factors consisting of 1 followed by the number of ciphers indicated by the Roman figure. In this way VI means a million, XII means a billion; similarly, XXI means a uno-twenty-one, which is about the number of gaseous molecules in each cubic centimeter of air at the bottom of our atmosphere.

which is the same as

$$v' = 11.015 \text{ km./sec.} \tag{10}$$

Now the rotation of the Earth carries station E' along at the rate of 0.478 km./sec. Hence a velocity

$$v' - u' = 11.015 - 0.478,$$
$$= 10.537 \text{ km./sec.},$$

will suffice, if the molecule be shot off in the direction in which it is already traveling in consequence of rotation. And, finally, if a strong west wind is blowing at station E', which must sometimes happen, a speed of

$$v' - u' - a = 10.5 \text{ km./sec.}, \tag{11}$$

may be enough. This, then, we may take to be the least velocity which enables molecules to escape from the Earth.

Let us now turn to what happens in gas. By Clausius' formula, p. 31,

$$w \text{ (the velocity of mean square in a gas)} = (111{\cdot}4)\sqrt{\frac{T}{\rho}} \text{ m./sec.},$$

which, at 66° below zero (which we regard as the temperature at station E') gives

$$w = (111{\cdot}4)\sqrt{\frac{207}{\rho}},$$
$$= 1603 / \sqrt{\rho} \text{ m./sec.}, \tag{12}$$

where w means the velocity of mean square in a gas at the temperature — 66° C.

If in this we put $\rho = 1$, we find

$$w = 1603 \text{ m./sec. in hydrogen.}$$

This is nearly a mile a second. Similarly putting $\rho = 2$, we find

$$w = 1133 \text{ m./sec. in helium.}$$

which is somewhat more than a kilometer per second. And, finally, if we put $\rho = 9$, we find

$$w = 534 \text{ m/sec., in the vapor of water,}$$

which is somewhat more than half a kilometer per second.

Now, we found above that, in order that any gas may cease to be imprisoned by the Earth, its molecules must now and then be able to attain at least a speed of 10.5 kilometers per second; see equation (11). Whenever this happens to a molecule favorably circumstanced it escapes. Hence, since hydrogen succeeds in leaking away from the Earth, its molecules must in sufficient numbers attain this speed, which is 6.55 times the velocity of mean square in that gas at a temperature 66° below zero; and since helium can escape, its molecules must sufficiently often reach a speed equal to or exceeding 9.27 times what we have found to be the velocity of mean square in helium at a temperature of —66° C.

On the other hand, in order that a molecule of water may escape from the Earth, it has to get up a speed of 19.66, nearly twenty times the velocity of mean square in that vapor at the above temperature: and the fact that water does not drain away from the Earth in sensible quantities shows that this seldom happens.

We are now in a position to make a very important deduction in molecular physics from these facts, which is that *in a gas a molecular speed of 9.27 times the velocity of mean square is reached sufficiently often to have a marked effect upon the progress of events in nature;* while, on the other hand, a molecular speed of twenty times the velocity of mean square is an event which occurs so seldom that it exercises no appreciable influence over the cosmical phenomena which we have been considering. We must remember, however, that there are other events in nature—in chemistry, and especially in biology—which may be, and probably are, determined by conditions that occur far more rarely.

The separation of the swiftest moving molecules from the boundary of our atmosphere is, of necessity, accompanied by a lowering *pro tanto* of the temperature of the atmosphere left behind. It is one of the many operations carried on by nature to which the second law of thermodynamics does not apply. We must remember that this law is only a law of molecular averages, and therefore is not a law of nature where, as in this case, nature separates one class of molecules (those moving fastest) from the rest.

CHAPTER V.

Extension of the inquiry to other bodies.—In order to extend our inquiry to the atmospheres upon other bodies of the solar system, we have to determine the potential of gravitation upon them. We can do this where r, the radius of the new body B, and m / M, the ratio of its mass to the mass of the Earth, are known. For then

$$k \text{ (the potential at the surface of } B) = \frac{m}{r}$$

$$= \frac{m}{M} \cdot \frac{R+h}{r} \cdot \frac{M}{R+h}, \tag{13}$$

of which the last factor is the K' which is given in a numerical form in equation (9).

Combining this with the dynamical equation (see p. 33)

$$k = v^2 / 2 \tag{14}$$

we can calculate v, which would be the minimum velocity of escape from B, if B were at rest. In general B rotates, and then the minimum velocity of escape is

$$v' = v - u, \tag{15}$$

where u, the velocity at the equator of B due to its rotation, is easily found, if we know from observation the period of rotation.

Having calculated v', we can determine what density a gas must have to escape from B with the same facility with which helium leaves the Earth. For this purpose, let w_1 be its velocity of mean square. Then, in accordance with what is stated on p. 37, w_1 may be as large as

$$w_1 = \frac{v'}{9{\cdot}27}, \tag{16}$$

where w_1 and v' are to be expressed in meters per second: and then Clausius's equation, viz.

$$w_1 = (111{\cdot}4)\sqrt{\frac{T}{\rho_1}} \text{ m. / sec.}, \tag{17}$$

enables us to calculate ρ_1 / T, *i.e.*, the density of that gas which, at a specified temperature T, can escape from B as freely as helium does from the Earth at a temperature of —66° C. This and all lighter gases will escape.

To determine what density of gas will be imprisoned by B as firmly as water is by the Earth, we proceed in a similar way. Here

$$w_2 = \frac{v'}{19{\cdot}66}, \tag{18}$$

and the rest of the work is the same as before, giving as its result the value of ρ_2 / T, where ρ_2 is the density of a gas which will find it as difficult to escape from B as water does from the Earth. It and all denser gases will be retained.

The investigation leaves uncertain the fate of gases whose density lies between ρ_1 and ρ_2.

CHAPTER VI.

Of the Moon.—When we turn to the Moon, we find the conditions to be such that it can rid itself of an atmosphere with much ease. Upon the Moon

r (its radius), ... = 1738 km.

$\frac{m}{M}$ (the ratio of its mass to that of the Earth), . = 0.01235

P (its period of rotation) . . . . . = 2,360,591 sec.

Calculating v', the least velocity which would enable a missile to quit the Moon by the equations in the last chapter, we find it to be about 2.38 km./sec., while on the Earth it is 11.015 km./sec., which, by the help of the rotation of the Earth and possible storm, may be, under favorable circumstances, furnished by a relative projectile velocity of 10.5 km./sec. Accordingly, more massive molecules can disengage themselves from the Moon with the same facility with which helium can leave the Earth, if ρ, their molecular mass, is greater than that of helium, in the ratio of the square of 10.5 to the square of 2.38, *i. e.*, if the molecules are 19.5 times heavier than those of helium, or, which is the same thing, 39 times heavier than those of hydrogen. Accordingly, hydrogen sulphide, with a molecular mass 17 times that of hydrogen, oxygen with a molecular mass of 16, nitrogen with a molecular mass of 14, and the vapor of water with a molecular mass of 9, will hurry away. They will all escape with greater facility than hydrogen does from the Earth. A like fate will befall argon with a molecular mass of 20, carbon dioxide with its molecular mass of 22, carbon disulphide with its molecular mass of 38, and all others of the gases emitted by volcanoes, or from fissures, of which the vapor density is less than 39. These will escape with greater promptness than does helium from the Earth.

This is what would happen if the Moon were by itself, and if portions of its surface could rise even to a temperature of — 66°C. But the conditions are more favorable. Lord Rosse infers from his observations that the temperature of the Moon's surface rises something like 280°C. when exposed to the fierce glare of the Sun's rays. Even if it shall turn out that this is an overestimate, it at all events makes it probable that the maximum temperature is very much higher than 207° above the absolute zero, which is the same as 66° below the freezing point. Moreover, the proximity of the Earth would somewhat assist the process at its present distance; and its greater proximity in former ages must have more assisted it. In fact, on this account, any of the gases or vapors in question which had been developed upon the Moon while the Moon was close to the Earth must have been for the most part transferred over to the Earth, if the Earth was then cool enough to retain them. Those molecules that have escaped from the Moon since its distance from the Earth became considerable have for the most part become independent planets traveling in a ring round the Sun, of which ring (roughly speaking) the Earth's path is the central line. There they are accompanied by most of the molecules of hydrogen and helium that have leaked away from the Earth. A very few of the latter which happened to be shot off at unusually high speed, and in the direction towards which the Earth was at the time traveling in its orbit, may have been able to disengage themselves altogether from the solar system; but this can have happened to but few of those thrown off from the Earth, and not to almost any of those ejected from the Moon.

CHAPTER VII.

Of Mercury.—The radius of Mercury may be obtained by assuming the equatorial radius of the Earth to be 6378 kilometers, and applying to it the data given in the preface to the *Nautical Almanac* for 1899. We thus find the planet's radius

$$r = \frac{3''\cdot 34}{8''\cdot 848} 6378 = 2406 \text{ km.}$$

The mass of Mercury is less satisfactorily known. We shall use the value

$$\frac{m}{M} = 0\cdot 065.$$

Mercury's rotation period is also in doubt. The difficult observations that have hitherto been made seem to be about equally consistent with a rotation period of nearly a day, and a rotation period of 88 days (the period of Mercury's revolution round the Sun). Possibly observations could be made in the daytime which would determine between these. Meanwhile

$u = 2$ m. / sec., if the rotation period is 88 days.

$u = 175$ m. / sec., if the rotation period is 1 day.

By using the above values for r and m / M in equations (13) and (14), we find

v (the minimum velocity of escape, if Mercury were at rest) = 4643 m. / sec.,

which is a little more than $4\frac{1}{2}$ km. / sec. Hence

$v' = v - u = 4641$ m. / sec., if the rotation period is 88 days,

and

= 4468 m. / sec., if the rotation period is 1 day.

By employing these values in equations (16) and (17), we find that

ρ (the density of the gas that will escape from Mercury, as freely as helium does from the Earth) . . = 10.25, on the 88-day hypothesis

and = 11, on the 1-day hypothesis,

and on the further supposition that the absolute temperature of the gas where it escapes is 207°, that is 66° C. below zero.

If the highest temperature at the upper surface of Mercury's atmosphere over his equator is higher than this, and it is probably much higher, the foregoing values for ρ will have to be increased in the ratio of $T / 207$, where T is the highest temperature reached. It must also be remembered that helium is so prompt in escaping from the Earth that it is probable that gases somewhat denser could escape; and, as a consequence, that the limiting density of the gases that can escape from Mercury has to be increased in the same proportion.

The general conclusion then is:

1. That water with a density of 9 certainly cannot exist upon Mercury. Its molecules would very promptly fly away.

2. That it is in some degree probable that both nitrogen and oxygen, with densities of 14 and 16, would more gradually escape.

It is, therefore, not likely that there are, in whatever atmosphere Mercury may be able to retain, any of the constituents of the Earth's atmosphere except perhaps argon and carbon dioxide.

CHAPTER VIII.

Of Venus.— The state of Venus' atmosphere need not detain us long. The potential of gravitation is so nearly the same on this planet as on the Earth that its atmosphere almost certainly retains and dismisses the same gases as does the atmosphere of the Earth. The only element of uncertainty arises from its period of rotation being imperfectly known, but the nearly globular form of the planet assures us that its rotation cannot be swift enough seriously to affect the problem.

The similarity of the two atmospheres is confirmed by the appearance of the planet. Venus is presumably a much younger planet than the Earth, and its temperature is consequently what the Earth's was many ages ago, when through excessive evaporation water was the largest constituent of our atmosphere, and when clouds were present everywhere and without intermission.

The conditions upon Venus are so nearly akin to those on the Earth that we cannot be mistaken in regarding the vapor which forms the abundant cloud we see on that planet as none other than the vapor of water. If we may assume this, we can advance a step farther than the statements made in Chapter IV.

The detailed computations in the case of Venus give

$$r = \frac{8''.40}{8''.848} 6378 = 6053 \text{ kilometers,}$$

$$\frac{m}{M} = 0.769;$$

and as such observations as are practicable seem to indicate that on that planet

$$P = 83779 \text{ seconds,}$$

we find that

$$v = 10000 \text{ m. / sec.,}$$
$$u = 454 \text{ m. / sec.;}$$

whence we infer that

$$v' = v - u = 9546 \text{ m. / sec.,}$$

is the least speed which will carry a projectile away from Venus.

Now, in water, $\rho = 9$. Whence, in accordance with Clausius' formula, p. 31, the velocity of mean square in water, at the temperature of $-66°$ C., is

$$w = \frac{1603}{\sqrt{\rho}} = 534 \text{ m./ sec.}$$

Now v' is almost exactly 18 times this value of w; so that the circumstance that Venus is able to retain its hold upon water means that the molecules of a gas do not attain a velocity 18 times that of mean square sufficiently often to enable the gas to escape from an atmosphere in appreciable quantities.

We are accordingly now in a position to go beyond the statement made on p. 314. We may now say:

1. A velocity of 9.27 times that of mean square is attained by the molecules of a gas sufficiently often to enable helium to escape from the Earth.

2. A velocity 18 times that of mean square is so seldom attained that Venus has been able to retain its stock of water.

3. Since Venus can prevent the escape of water, the Earth, with its larger potential, is competent to retain its hold upon a gas of somewhat less density, viz., one whose density is $\rho = 7.43$.

Accordingly, as regards the Earth, we may come to the following conclusions: (1) Gases with a density of 2 or less than 2 can certainly escape from the Earth; (2) a gas with a density of 7.43, and all denser gases,[1] are effectually imprisoned by the Earth; (3) the information supplied by Venus, supplemented by our present chemical knowledge, does not determine what would be the fate of a gas, if there be such, whose density lies between 2 and 7.43.

CHAPTER IX.

Of Mars.—The case of Mars is one of exceptional interest. Using the data furnished by the *Nautical Almanac*, we find its radius to be

$$r = 3372^{\text{km}}.$$

As in the case of Mercury, its mass is not yet known with exactness. It has become better known since observations have been made on the elongations of its satellites, which seem to furnish the value:

$$\frac{m}{M} = 0.1074.$$

Its period of rotation is known, viz., 88,643 seconds; whence, and from its radius, we find

$$u \text{ (the velocity at the equator due to rotation)} = 239^{\text{m}}/\text{sec.}$$

By following the same steps as in the case of Mercury, we find successively

$$v = 5042^{\text{m}}/\text{sec.},$$

[1] Ammonia NH_3, and Methane CH_4, are a little above this limit, and therefore can neither of them escape. Ammonia is no doubt washed out of the Earth's atmosphere by rain; but it is not easy to see what becomes of the methane. It seems unlikely on chemical grounds that it directly combines with oxygen, furnishing water and carbon dioxide. Possibly it meets with a trace of. chlorine, and furnishes methyl chloride and hydrogen in the presence of sunshine; or possibly it is nitro-methane that is formed.

for the least velocity which would carry a missile away from Mars, if Mars were not rotating, and

$$v' = v - u = 4803^{\mathrm{m}}/\mathrm{sec.},$$

for the relative velocity which is sufficient in consequence of the rotation.

From this, and equations (16) and (17), we find

$$\rho = 9.57,$$

as the density of a gas which would escape from Mars at a temperature of $-66°$ C., with the same facility as helium from the Earth. Hence, and since $9.57 : 9 = 207 : 194.7$, it follows that water would quit Mars at the absolute temperature of 194.7°, that is at $-78.3°$ C., as freely as helium can escape from the Earth at the temperature of $-66°$ C.

We must make some allowance for the probability that the highest temperature at which a gas has an opportunity of escaping from Mars may be lower than the corresponding temperature on the Earth. And we must, on the other hand, remember that the molecules of helium are almost certainly not quite the heaviest molecules that can rid themselves of the Earth. Taking both considerations into account, *it is legitimate to infer that water, in which* $\rho = 9$, *cannot remain on Mars.*

As to what happens to gases with densities of 14 and 16, we cannot speak with confidence. They may perhaps be imprisoned. And the conspicuous polar snows of Mars make it in a considerable degree probable that carbon dioxide, of which $\rho = 22$, is abundantly present.

It appears here to be worth reviewing the state of things that must prevail if the atmosphere of Mars consists mainly of nitrogen and carbon dioxide. Without water, there can be no vegetation upon Mars, at least not such vegetation as we know; and, in the absence of vegetation, it is not likely that there is much free oxygen. Under these circumstances, the analogy of the Earth suggests that the atmosphere of Mars consists mainly of nitrogen, argon, and carbon dioxide.

Carbon dioxide, the most condensible gas of such an atmosphere, would behave very differently from the way in which water behaves on the Earth. Water in the state of vapor is so much lighter than the other constituents of our atmosphere that it hastens upward through the atmosphere; and, accordingly, its condensation into cloud, whether of droplets of water or spicules of ice, takes place usually at very sensible elevations. There would be no such hurry to rise on the part of carbon dioxide, it would, on the contrary, show great sluggishness in diffusing upward through an atmosphere of nitrogen. When brought to the ground in the form of snow or frost (for there would probably be no rain), and when subsequently evaporated, the carbon dioxide gas would crawl along the surface, descending into valleys, occupying plains and pushing its way under the nitrogen, mixing only slowly with the nitrogen; and, as a result, only a very small proportion of the whole stock would be at any one time found elsewhere in the atmosphere than near the ground. It is suggested that the fogs, the snows, the frosts, and the evaporation of such a constituent of the atmosphere may account for the peculiar and varying appearances upon Mars, which, though recorded in our maps as if they were definite, are in reality very imperfectly seen from our distant Earth. In fact, Mars, when nearest the Earth, which unfortunately seldom happens, is still 140 times farther off than the Moon. Fogs over the low-lying plains which on Mars correspond to the bed of our ocean, with mountain chains projecting through the fog, and a border of frost along either flank of these ranges, would perhaps account for some of the appearances which have been glimpsed; and extensive displacements of the vapor, consequent upon its distillation towards the two poles alternately, would perhaps account for the rest.

CHAPTER X.

Of Jupiter.—In the case of the planet Jupiter, we have the following data:

$$r \text{ (Jupiter's equatorial radius)} = \frac{97''\cdot 36}{8''.848} 6378 = 70170 \text{ km},$$

P (the periodic time of his rotation) = 35,728 seconds,

$\frac{m}{M}$ (m being Jupiter's mass, and M the mass of the Earth) = 311.9.

Using these data we find—

u (the velocity at his equator, owing to the rotation) = 12.337^{km} / sec.,

v (the least velocity which would carry a missile away, if Jupiter were not rotating) = 59.570^{km} / sec.,

$v' = v - u$ (the least velocity which enables a missile to escape when helped by the rotation) = 47.233^{km} / sec.,

ρ_1 (the density of gas which would escape from Jupiter, at a temperature of −66° C., with as much ease as helium does from the Earth) = 0.099 of the density of hydrogen,

ρ_2 (the density of a gas which would be imprisoned by Jupiter as effectually as water is by Venus) = 0.373 of the density of hydrogen.

Hence gases with a density less than $\frac{1}{10}$ of that of hydrogen (if any such exist) could escape from Jupiter. But Jupiter can prevent the escape of a gas which has a density a little more than a third of the density of hydrogen, and of all denser gases.

Jupiter is accordingly able to imprison all gases known to chemists. His atmosphere may therefore, so far as can be determined by the present inquiry, have in it all the constituents of the Earth's atmosphere, with the addition of helium and hydrogen, and any elements between hydrogen and lithium which the Earth may have lost; except that, if the hydrogen is sufficiently abundant, there can be no free oxygen. Owing to the chemical reaction that would then take place, the oxygen will have been used up in adding to the stock of water.

CHAPTER XI.

Of Saturn, Uranus, and Neptune.—Our information with reference to these three planets is less satisfactory. Computing their radii from the data given in the *Nautical Almanac*, we find

r = 61060 km. on Saturn,
= 24700 km. on Uranus,
= 26340 km. on Neptune.

Their masses compared with the masses of the Earth are also sufficiently known, viz.:

$$m/M = 93.328, \text{ for Saturn,}$$
$$= 14.460, \text{ for Uranus,}$$
$$= 16.863, \text{ for Neptune;}$$

but their rotation periods are very imperfectly known. We shall take them to be about

$$P = 36864 \text{ seconds, of Saturn,}$$
$$= 36000 \text{ seconds, of Uranus,}$$
$$= 36000 \text{ seconds, of Neptune.}$$

If we may use these values, we find

$$u = 10.412 \text{ km./sec., on Saturn,}$$
$$= 4.311 \text{ km./sec., on Uranus,}$$
$$= 4.598 \text{ km./sec., on Neptune,}$$

for the velocity at the equator due to the planet's rotation. Further, by equations (13) and (14), we find for the minimum velocity of escape from each of these planets, if not rotating,

$$v = 34.92 \text{ km./sec., on Saturn,}$$
$$= 21.61 \text{ km./sec., on Uranus,}$$
$$= 22.60 \text{ km./sec., on Neptune;}$$

whence

$$v' = v - u = 24.508, \text{ on Saturn,}$$
$$= 17.299, \text{ on Uranus,}$$
$$= 18.002, \text{ on Neptune,}$$

is the least velocity which enables a missile to escape when helped by the rotation.

By dividing these last numbers by 9.27, we find the velocity of mean square of the gas which can escape as freely as does helium from the Earth, and then by Clausius' formula, we can calculate ρ_1, its density, which is

$$\rho_1 = 0.37 \text{ of the density of hydrogen on Saturn,}$$
$$= 0.74 \text{ of the density of hydrogen on Uranus,}$$
$$= 0.68 \text{ of the density of hydrogen on Neptune.}$$

On the other hand, by dividing the values for v' by 18, we learn what is the velocity of mean square of the gas which would be detained as firmly as water is held by Venus; and then, if we calculate ρ_2 by Clausius' formula, we find

$\rho_2 =$ 1.39 times the density of hydrogen on Saturn.
$=$ 2.78 times the density of hydrogen on Uranus.
$=$ 2.57 times the density of hydrogen on Neptune.

Now hydrogen, with a density of 1, stands in each case between ρ_1 and ρ_2, and we are, therefore, left uninformed whether hydrogen is or is not allowed to escape. There is, perhaps, some ground for conjecturing that it cannot escape from Saturn, and that it can escape from Uranus and Neptune. But this must remain doubtful. Helium, with its density of 2, being more than the value of ρ_2 upon Saturn, is certainly imprisoned by that planet, but we have no satisfactory information as to what is its fate upon Uranus or Neptune.

Thus the information we gain with reference to these three planets amounts to this—that we have no definite information as regards hydrogen; that Saturn is able to detain helium, but that we do not know whether the other two planets can or cannot; that all other gases known to chemists would be more firmly imprisoned by any one of these planets than they are by the Earth; and that, if there be gases lighter than hydrogen, it is certain that Saturn cannot detain any of which the density falls as low as one-third of that of hydrogen, Neptune cannot hold any as light as two-thirds, nor Uranus any lighter than three-quarters of the density of hydrogen. On the whole, the probability seems to be that the atmosphere of Saturn is nearly the same as that of Jupiter; while the atmospheres of Uranus and Neptune more nearly approximate to that of the Earth, with perhaps the addition of any gases with densities less than 7.43 that may possibly have left the Earth when the Earth was hotter, and whose withdrawal from the Earth is perhaps what has left the gaps in the series of terrestrial elements which appear to exist between hydrogen and helium, and between helium and lithium.

CHAPTER XII.

Of the satellites and minor planets.—We have no sufficient information as to the densities of any these bodies. But the asteroids, or minor planets, which lie between the orbits of Mars and Jupiter, are all of them bodies so small that, even if they were as dense as osmium, iridium, or platinum, they could not retain their hold upon an atmosphere. The same may be said of the two satellites of Mars, of the two satellites of Jupiter, of most of the satellites of Saturn, and of the small bodies that make up the rings of Saturn. None of these can condense any atmosphere upon them. If there are molecules of gases traveling in their neighborhood, they also are, each of them, an independent satellite.

One satellite of Saturn and three of Jupiter are larger than our Moon; and one other of Saturn and one of Jupiter, though smaller than the Moon, are not much smaller. We should need to know the densities of these bodies before we could speak with confidence about them. The presumption, however, is that, as their primaries are very much less dense than the Earth, so these satellites are probably less dense than the Moon. If so, they also, as well as the smaller satellites, must be devoid of atmosphere.

We know too little about the satellites of Uranus and Neptune to venture upon any conclusion about them. The satellite of Neptune appears to be a body of considerable size, and, with some probability, it may have an atmosphere.

CHAPTER XIII.

What becomes of the molecules that escape.—The speed of the Earth in its orbit is about 30 km./sec. Now it follows, from the dynamics of potential, that the potential of the Sun at the distance of the Earth is represented by the square of this number if the Sun's mass be measured in gravitational units. That is

$$k = \frac{m}{r} = 900,$$

where m is the mass of the Sun, and r the radius of the Earth's orbit.

We have already found, on p. 35, the potential of the Earth at the boundary of our atmosphere to be

$$K' = \frac{M}{R+h} = \frac{v'^2}{2} = \frac{121}{2} = 60{\cdot}5.$$

Therefore the joint potential of the Sun and Earth at that station is

$$\frac{m}{r} + \frac{M}{R+h} = 960{\cdot}5.$$

This, then, is equal to $v^2/2$, when v is the least velocity which would enable a missile to escape from both these bodies if stationary. Therefore

$$v = \sqrt{(2 \times 960{\cdot}5)} = 43{\cdot}83 \text{ km.} / \text{sec.}$$

If the missile be shot off in the direction towards which the Earth is traveling, it has already got, in common with the rest of the Earth, 30 km./sec. of this velocity; and therefore, if fired off in that direction, the speed with which it would need to part from the Earth is 13.83 km./sec. Accordingly, this is a velocity which would suffice to set the molecule completely free, if the Earth were arrested in its orbit immediately after the molecule left it. But since, on the contrary, the Earth persists on its course, a slightly greater speed of projection is actually needed. Now, as 11 km./sec. is enough to enable a molecule to leave our atmosphere, it can be but very seldom that a molecule quits it with a velocity somewhat exceeding 13.83 km./sec.; and, accordingly, nearly all the molecules that have left the Earth have remained in the solar system, and are in fact now traveling as independent planets round the Sun.

We have taken the special case of a molecule leaving the Earth's atmosphere. A similar treatment applies to molecules leaving the atmospheres of other planets and satellities. In every case the velocity required to enable a molecule to quit the solar system is markedly in excess of that which enables it to escape from its own atmosphere. Accordingly, almost all such wandering molecules are still denizens of the solar system.

CHAPTER XIV.

Former size of the Sun.—The Sun is contracting, and therefore in past time was larger than it now is. The question then arises, how much larger may it have been while it was still globular? We can place a limit on its possible size *if we assume that it was then, as now, able to prevent the escape of free hydrogen*, and if we assign a temperature below which its outer boundary did not fall.

In order to arrive at definite results, let us suppose this temperature to be 0°C. Here we might take into consideration the probability that, at a sufficiently remote period, the planets formed part of the Sun. But it is needless to do this, as the addition to be then made to its present mass would be only about $\frac{1}{750}$ part, which is too slight an increase sensibly to affect our present computation.

We have first to ascertain what the "velocity of mean square" of hydroden is at the freezing temperature. It is got by putting $T=273$ and $\rho=1$ into Clausius' formula, page 310. We thus find $w=1.841$ km./sec. This multiplied by 9.27 (see page 314) gives us a velocity v_1 which the molecules of hydrogen could, at this temperature, get up sufficiently frequently, for the purpose of escape. And if multiplied by 18 (see page 320), it furnishes a velocity v_2 which hydrogen is unable to get up sufficiently frequently for effective escape. We thus find

$$v_1 = 17^{\text{km}}/\text{sec.} \quad , \quad v_2 = 33.14\ {}^{\text{km}}/\text{sec.}$$

We have next to find how large the Sun should be in order that one or other of these velocities should be that which is just sufficient for the escape of a molecule. For that, r_1 and r_2 being the corresponding radii, the potentials must amount to

$$\frac{m}{r_1} = \frac{17^2}{2} = 144.5, \quad , \quad \frac{m}{r_2} = \frac{(33.14)^2}{2} = 549.$$

But at the distance of the Earth we found $m/r=900$. Therefore

$$\frac{r_1}{r} = \frac{900}{144.5} = 6.227, \qquad \frac{r_2}{r} = \frac{900}{549} = 1.64.$$

That is, the surface of the Sun would need to have been about $6\frac{1}{4}$ times farther from the Sun than the Earth now is, in order that hydrogen at 0°C. should escape from it as freely as helium does from the Earth at —66° C. And it would need to have been 1.64 times farther than the Earth to imprison the hydrogen as firmly as water is held by Venus.

Hence, the *greatest* size which the Sun can have had since it became a sphere, consistently with its not allowing hydrogen at 0° C. to escape, is an immense globe extending to some situation intermediate between the orbits of Mars and Jupiter. From some such vast size it may have been ever since slowly contracting.

CHAPTER XV.

Of motions in a gas.—In carrying on an inquiry such as that of the present Memoir, we should keep in mind that the encounters between molecules have not the same effect on their subsequent motions as mere collisions between elastic or partially elastic solids would have. Let us, for simplicity, picture to ourselves two molecules which approach one another along a straight line, and after an encounter, which is in fact a complex struggle, recede from one another along the same line.

If they were solid particles with elasticity e, the equations of their motion would be

$$m_1 u_1 + m_2 u_2 = m_1 v_1 + m_2 v_2,$$
$$u_1 - u_2 + e(v_1 - v_2) = 0,$$

where $v_1 v_2$ are the velocities before, and $u_1 u_2$ the velocities after, the collision, and where e, the coefficient of elasticity, depends on the amount of the kinetic energy which is expended on internal events during the collision. It is therefore necessarily a proper fraction; so that e, in the case of solid particles, cannot exceed 1, whereas, in the encounters between molecules, it may have any value whether above or below 1. This is because, during an encounter between molecules, energy is in some cases imparted to, and in other cases withdrawn from, the motions of the molecules along their free paths, whereas, in a mere collision, energy is always withdrawn. In fact, the *internal* events of individual molecules are in communication with heat motions in the ether, and interchange energy with it. A molecule may thus absorb energy from the ether during the whole of the long flights which it makes, when near the top of an atmosphere, between its encounters; and any excess of energy thus acquired will be shared with the motions of translation of the molecules when the next encounter takes place. Accordingly, the value of e will vary from one encounter to another, and, near the boundary of an atmosphere, there may be changes in the velocities of the molecules which are more abrupt than in situations where the gas is denser.

The effect here spoken of would be more marked in the case of helium, water, nitrogen, or oxygen, than in that of hydrogen, inasmuch as solar rays of the kind that hydrogen can absorb reach the Earth in a feebler state than those which the other gases absorb, owing to the partial absorption by hydrogen which has already taken place in the hot outer atmosphere of the Sun. On this account the rays that can affect hydrogen are the relatively feeble radiations from Fraunhofer lines, whereas the molecules of the other gases are exposed on the confines of our atmosphere to the glare of full sunshine. This is evidenced by the Earth-lines of the solar spectrum, especially those due to oxygen and aqueous vapor.

These considerations were taken into account in fixing on -66° C. as the maximum temperature to be attributed to the outer layer of our atmosphere. No doubt it would, in some slight degree, improve the investigation to use a rather lower temperature in the solitary case of hydrogen; but it was not thought necessary to make a distinction of this kind in an investigation which, from the nature of the case, could only be approximate. The only effect of introducing the refinement would have been to show that the facility with which hydrogen escapes from an atmosphere is not quite so much in excess of the facility with which helium escapes as the numbers in Chapter IV indicate. This is almost certainly true to some small extent; but it leaves our main conclusions undisturbed. Accordingly, the simpler mode of inquiry, in which these and other small differences are ignored, has been an adequate investigation for our purpose.