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THE ATMOSPHERES OF THE PLANETS[1]

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Two ways are open to the retiring president of this association, when he makes what small return he can for the honor of his election. By a sound and time-honored custom, it is his duty and privilege to speak of some topic, within his own technical field, but of general interest. He may therefore either report on his own researches—if he is fortunate enough to have recent or unpublished results good enough to measure up to the standard of a presidential address—or he may survey some section of his part of the field of science in which important gains have lately been made, though his own contribution to this advance may be small. Only the latter course is open to the present speaker: and so, this evening, we may devote a little time to the atmospheres of the planets.

As soon as telescopes became good enough to give a tolerable view of details on the planets, evidence began to accumulate that some of them, at least, possessed atmospheres. Doubtless the first to be noticed were the changes in the markings on Jupiter, which differ radically from one year to the next, and often appear suddenly and last but a few weeks, though thousands of miles in diameter. Only clouds, forming and dissolving in a Jovian atmosphere, can account for such rapid and capricious changes.

Evidence for an atmosphere on Mars is afforded by the polar caps. The steady shrinkage of these during the summer, accompanied by the growth of the opposite cap during the long, cold polar night, is explicable only by the melting or evaporation of deposits of some snow-like substance, which is carried as invisible vapor to the opposite pole, and there deposited. A permanent, non-condensible atmosphere is required for the transport of this vapor.

Venus, when she is considerably nearer to the

[1] Address of the retiring president of the American Association for the Advancement of Science, Pittsburgh, December 31, 1934.

earth than to the sun, shows a crescent phase, like that of the moon, and for the same reason. As she comes more nearly into line between us and the sun, her crescent narrows, and the horns begin to project beyond their normal positions, so that she has been seen as three quarters of a circle, and even as a thin bright ring, with a dark interior. This remarkable phenomenon can be seen only when Venus is within about a degree of the sun, and no chance to observe it again will occur till near the end of the present century; but it has been recorded in the past by several competent observers. Such an extension of the horns—and, above all, the ring-phase—can be explained only as effects of twilight, the illuminated atmosphere of the planet being visible across the narrow dark strip of its surface on the side farther from the sun.

For the three brightest planets, then, the presence of an atmosphere is proved by observation, in three quite different, but equally conclusive ways, all of which were well known to astronomers before the end of the eighteenth century.

Later observations have added evidence of the same type—a few white spots on Saturn, appearing at irregular intervals of some decades, which change shape, shift and disappear as clouds would do; occasional though fugitive clouds, and a measurable effect of twilight, upon Mars; and elusive markings on Venus, which can be photographed only with ultra-violet light, and change greatly between one evening's observations and the next. The extent of atmosphere can also be roughly estimated from the results of direct telescopic observation. The surface details of Jupiter (and of Saturn when any appear) may be seen, and photographed, close up to the limb, despite the very oblique angle of view. It is therefore evident that there can be no such extensive gaseous mantle as veils the earth. At least, there is none above the visible cloud-surfaces of these great planets—how much there may be below is another matter. The rarefied layer which exists, however, suffices to cut down the apparent brightness of the edge of the planets' disks. The effect of contrast against a dark sky conceals this in an ordinary telescopic view; but the first look at one of these planets in strong twilight shows that it is actually of surprising magnitude.

There is more "limb-light" on Mars, and there may be more atmosphere above the visible surface—the real surface, this time; but an atmosphere as thick as the earth's, even if free from clouds or haze, would produce a much greater effect.

For Venus the layer which produces the elongation of the crescent is remarkably thin, rising only about 4,000 feet above the visible surface. But this represents only the part of her atmosphere which is hazy enough to be seen through the glare of our own sky close to the sun. The top of the atmosphere must be much higher; and the bottom, if the visible surface is composed of clouds, much lower, so that its whole amount may be great.

The celestial body which we can observe in far the greatest detail tells quite another story. The moon, viewed telescopically, shows no more atmosphere—whether in the artist's or the physicist's sense—than a bare plaster cast illuminated by a powerful searchlight. Far more delicate tests are possible here than in other instances, and neither refraction nor twilight is present to the minutest degree. Our satellite is naked rock *in vacuo*. Mercury, too, appears to be without an atmosphere, though the evidence is less detailed.

The existence of atmospheres on the majority of the planets—though not on all—is thus established by direct telescopic observation. To determine their composition, we must, as usual, have recourse to the spectroscope: but we meet with two difficulties.

In the first place, many possible atmospheric constituents show no selective absorption whatever in the region accessible to our study. Hydrogen, nitrogen, helium, neon and argon belong in this group, and are hopelessly beyond the reach of our investigation. Secondly, the other gases of the earth's atmosphere absorb too much for our advantage. The worst by far is ozone. Though present in but small amounts, and mainly in the higher layers, it cuts off the whole spectrum short of 2,900 Angstroms, and deprives us of any hope of studying the most interesting parts of all celestial spectra.

Were we working in the infra-red, water-vapor would be almost as troublesome. There are long stretches of the solar spectrum, within the range of present-day plates, in which we can find out little or nothing about the sun's own spectrum. The great wide lines of the water-vapor bands, often overlapping, hide almost everything else. The band near 11,500 A is quite hopeless; that at 18,000 would be worse, if our photographs got so far; one near 9,600 is still very bad; while in those near 8,200 and 7,200 the solar lines can be picked out, with care, among their stronger telluric neighbors.

Oxygen reveals itself by a strong band, with very regularly spaced lines, at λ 7,594 (Fraunhofer's A), the weaker B band near 6,867, and the much fainter α band at 6,277. The terrestrial origin of all these lines is conclusively settled by two tests: first, their changes with the altitude of the sun (varying the air-path) and, for the water-vapor lines, with weather conditions; second, the absence of the Doppler shift, due to the sun's rotation, when light from the east and west limbs is compared. The absence of even faint components of solar origin is explained by the high temperature, which dissociates such molecules completely.

The intensities of these bands are in inverse order of the abundance of the molecules which produce them —an apparent anomaly, explained by the circumstances of their origin. The ozone band is part of the main system of the O_3 molecule, and, like all such bands, is very intensely absorbed, a layer of the gas, at its worst, being as opaque as one of metal of equal mass per square centimeter. For water-vapor the main absorption bands lie far in the infra-red, and are very strong—those with which we are now concerned involve high harmonics of the fundamental vibrations. The coefficient of absorption, and the intensity of the bands, diminishes rapidly with increasing order of the harmonics and diminishing wave-length.

The oxygen bands are produced by a "forbidden" transition within the molecule, for which the probability of absorption is exceedingly small. This is why the whole mass of oxygen above our heads (equivalent to a layer two kilometers thick at standard temperature and pressure) produces absorption lines no stronger than the sodium vapor in a Bunsen flame an inch thick, which contains but a minute percentage of the vapor of the metal. The principal bands of oxygen, in the ultra-violet beyond λ 1,800, are so strong that light of shorter wave-length can not be observed at all in air. The experimenter must put his whole spectroscope in a gas-tight case, and pump it out to an almost perfect vacuum.

In the visible spectrum, the portions cut out by oxygen or water-vapor are very small in extent; but they come exactly in the wrong place—in other words, they hide, line for line, absorption by these same gases which might be produced in the atmosphere of a planet.

If the planet's atmosphere was decidedly richer in either constituent than the earth's, we might detect the fact, for the lines in the planet's spectrum would be stronger than in that of the moon. Comparisons of this sort, however, must be made with great precautions. The moon and planet must be at the same altitude when the observations are made (to get equal air-paths). It is not safe, either, to observe the planet early in the evening and wait till the moon rises to the same height, for a change in temperature may have caused the precipitation of water out of the air, though the oxygen, of course, remains the same. With sufficient patience, a time may be found when planet and moon can be seen together, at equal altitudes, and observed almost simultaneously, with the same instrument.

Early observations of this sort were supposed to show the presence of oxygen and water-vapor on Venus and Mars; but the careful and accurate work of Campbell, in 1894, led him to the conclusion that there was no perceptible difference in the strength of the bands in the two cases, and hence that the amounts of these two important substances, above the visible surfaces of either planet, did not exceed one fourth of those above an equal area of the earth's.

A more delicate, and very ingenious, test was invented, independently, by two distinguished American observers, Lowell and Campbell. When Mars (or Venus) is approaching us, or receding, most rapidly, the lines in its spectrum are displaced by the Doppler shift, while lines produced in the earth's atmosphere are of course unaffected. Were this shift great enough the planetary and telluric lines would appear double, and the former, even though faint, could readily be detected. The greatest available shift is not enough to resolve the lines completely; but measures of the blended lines suffice to show whether any important planetary contribution is present. A still more delicate test is afforded by microphotometer measures of the contours of the lines, which would reveal even a slight asymmetry. These observations are very exacting—requiring high dispersion and a great deal of light—so that the best evidence is that from the great coudé spectrograph of the 100-inch telescope at Mount Wilson. St. John and Nicholson found, in 1922, that there was no perceptible trace of planetary lines in Venus, and Adams and Dunham, in 1934, have come to the same conclusion in the case of Mars. An amount of oxygen, on either planet, equal to a thousandth part of that above an equal area on earth, could certainly have been detected. For water-vapor, the tests have so far been less delicate, and are not fully decisive—though the quantity present on either planet must be small. More delicate tests, with stronger lines, may soon be made on new red-sensitive plates.

There can be no reasonable doubt, on quite different evidence, that some small amount of water-vapor is actually present in Mars' atmosphere. Radiometric observations of the planet's heat show definitely that the surface rises to temperatures above 0° Centigrade at noon every day in the Martian tropics, and at the pole at midsummer, though falling far below freezing at night. The polar caps must therefore really be composed of snow, and evaporate into water-vapor, even if the pressure is so low that the ice turns directly into vapor without melting. The only plausible alternative suggestion—carbon dioxide—would volatilize at much lower temperatures than the actual polar caps do. But, judging from the amount of solar heat available to evaporate them, the polar caps must be very thin—probably only a few inches thick. The vapor resulting from the gradual sublimation would never attain any considerable density, and might easily fail of detection by the tests which have so far been practicable.

No such independent evidence is available for Venus, but Adams and Dunham, in 1932, discovered, in the infra-red region of her spectrum, three beautifully defined bands with heads at λ 7,820, λ 7,883 and λ 8,689, and evidently of atmospheric origin. They had not then been observed elsewhere; but an immediate suggestion regarding their origin was obtained from the theory of band-spectra—by that time well developed. The spacing of the individual lines in a band arises from the rotation of the molecule and depends upon its moment of inertia. For the new planetary band, it showed that the otherwise unknown molecule involved must have a moment of inertia of 70.5×10^{-40} c. g. s. units. This agreed almost exactly with that of the molecule of carbon dioxide—already known from laboratory observations in the infra-red. All doubt regarding this identification was removed when Dunham, passing light through 40 meters of CO_2 at a pressure of 10 atmospheres, found that the strongest of the bands found in Venus was faintly absorbed. Recently Adel and Slipher, using a path of 45 meters through gas at 47 atmospheres' pressure, have found the bands considerably weaker than they appear in the planet. They conclude that the amount of carbon dioxide above the visible surface of Venus is at least two mile-atmospheres—that is equivalent to a layer two miles thick at standard atmospheric pressure and temperature. The whole amount above the planet's solid crust may be much greater. For comparison it may be noted that the whole atmosphere of the earth amounts to five mile-atmospheres, and the oxygen in it to one and a quarter.

These bands do not show in the solar spectrum, even when the sun is setting. But there is very little CO_2 in the earth's atmosphere, and the whole amount in the path, even at sunset, amounts to only thirty feet under standard conditions.

The weak absorption in these bands, like that in the visible bands of water-vapor, arises because they involve high harmonics of the fundamental vibration-frequencies—in this case the fifth.

So far we have had to do with bands of familiar and readily identified molecules; but the major planets have been much more puzzling.

Jupiter shows a conspicuous band in the orange, which was discovered visually by Huggins in the earliest days of spectroscopy, and fainter ones in the green. These appear more strongly in Saturn, but only in the spectrum of the ball of the planet, and not at all in that of the ring—which might be anticipated, since the ring consists of a multitude of tiny isolated satellites, and should be quite devoid of atmosphere. Uranus, though its light is faint, shows the same bands, much more strongly, and many others in addition. One of these, which closely coincides with the F line of hydrogen (λ 4,861) led Huggins to conclude that the planet's atmosphere was rich in hydrogen.

This interpretation, though quite permissible at the time, was erroneous, for the line is absorbed only by dissociated *atoms* of hydrogen, which will not be present except at very high temperatures.

The bands cut out so much of the red and orange light that the whole disk of Uranus appears decidedly green—an unusual color, noticed from the time of the planet's discovery.

In Neptune's spectrum, the bands are of enormous strength, cutting out the red almost entirely and making the planet look still greener. They are hard to observe visually in so faint an object, and the full realization of their intensity came only with the admirable photographs of V. M. Slipher, in 1907. In later years, and with modern plates, Slipher has extended his observations far into the red, finding bands of ever-increasing strength—up to λ 10,000 for Jupiter, where there is light enough to follow the spectrum farthest.

For more than sixty years after their first discovery, and twenty-five after Slipher's spectrograms, these bands presented one of the principal unsolved puzzles of spectroscopy—for no one had duplicated them in the laboratory. To be sure, one group, near λ 7,200, agrees fairly well with a band of water-vapor—but the still stronger water-bands deeper in the red are absent, so that this must be a chance coincidence.

When the radiometric measures of Coblentz and Lampland, and of Nicholson and Pettit, showed that the temperature of the visible surfaces of Jupiter and Saturn must be well below $-100°$ Centigrade—while Uranus and Neptune are doubtless colder—the range of possibilities was very much narrowed. But it was not until 1932 that a young and brilliant German physicist, Rupert Wildt, realized the solution of the problem.

Other gases, like water-vapor and carbon dioxide, have strong fundamental absorptions in the infra-red, and fainter harmonics in the more accessible part of the spectrum, which demand a long absorbing path in the laboratory to bring them out. Utilizing observations of this sort, Wildt showed that certain bands in the spectrum of Jupiter near λ 6,470 and λ 7,920 agreed with those of ammonia, and others, at λ 6,190, λ 7,260 and λ 8,860, with bands of methane. The original comparison was not quite conclusive, for with the moderate dispersion then employed the planetary bands had not been adequately resolved into their component lines. This was soon accomplished by Dunham, who found so complete a coincidence of the accurately measured individual lines that both identifications were put beyond all question. For ammonia more than sixty lines were found to agree, and for methane 18 lines in part of one band. Some expected band lines were naturally blended with solar lines, but not one of importance failed to appear.

From these comparisons Dunham estimates that the quantity of ammonia gas above the visible surface of Jupiter is equivalent to a layer ten meters thick under standard conditions. In Saturn it is less.

The climax of the tale came this year, when Adel and Slipher announced that practically all the bands had been identified, and were due to methane. The 45-meter path and the 40-atmosphere pressure got enough of the gas into the way of the light to produce bands intermediate in intensity between those in Jupiter and in Saturn. At this high pressure the lines flowed together, and produced diffuse bands; but the agreement of these with the planetary bands was so complete as to be decisive.

A further, and wholly conclusive, test could be added. The fundamental frequencies of vibration of the methane molecule were already known, from observations in the infra-red. For the higher harmonics of these vibrations the frequencies are not exact multiples of the lowest, but nevertheless bear a simple numerical relation to them (as is well known in the case of other gases). Applying this test, the strongest bands (including Huggins' band in the orange, and the one coincident with the blue hydrogen line) were found to be harmonics, from the third to the eighth, of one of the fundamental frequencies, while another slower vibration was represented by all its harmonics from the eighth to the sixteenth. The remaining bands were accounted for by combinations of these harmonics with other known frequencies, all of types consistent with the well-established rules which govern band spectra. Thirty-six bands in all have been identified. Many of these appear only in Uranus and Neptune, and have not yet been produced in the laboratory, but the harmonic relations just mentioned make their identification certain. The higher gaseous hydrocarbons, ethane, ethylene and acetylene, all have bands in places clear of disturbance by the methane; and all were looked for in vain. All the planetary bands of any importance are accounted for by methane alone—it is a clean sweep.

From the published data, it appears that the amount of methane above the visible surface of Jupiter is of the order of one mile-atmosphere. There must be much more on Uranus, and especially on Neptune; but we can not yet estimate its amount.

There is still plenty of work to do upon these bands, but mainly for the theoretical investigator. Adel calculates that the band at λ 5,430, when fully resolved, should consist of eighteen different overlapping systems of many lines each. Fortunately, the astrophysicist need not wait to draw his conclusions till this has been completely analyzed.

The results of observation can be summarized in a sentence. Large planets have atmospheres containing hydrogen compounds; middle-sized planets, atmospheres containing oxygen compounds; and small planets no atmospheres at all. The reason, in the last case, was found by Johnstone Stoney, in 1897. It is simply that small bodies have not sufficient gravitative power to keep their atmospheres from diffusing away into the vacuum of interplanetary space. At the surface of any planet, there is a certain velocity of escape, depending only on its mass and radius. A body projected from its surface, in whatever direction, with this or any higher velocity, will fly off in a parabolic or hyperbolic orbit and never return—unless, indeed, it meets with some obstacle or resistance on its outward way. For the moon this velocity is 2.4 kilometers per second; for the earth, 11.2; for Jupiter, 60.

Now the molecules of any gas are continually flying about in all directions, with average speeds which depend upon their weights. At zero Centigrade the average speed for a hydrogen molecule is 1.84 km/sec; for oxygen, 0.46; for carbon dioxide, 0.39. If an atmosphere of hydrogen could be put upon the moon, every molecule that was moving but a little faster than the average would fly off at once into space, unless it was thrown back by collision with another, and the atmosphere would diffuse away in a very short time. With an escape velocity three times the average speed, enough fast-moving molecules would get away to reduce the atmosphere to half its original amount in a few weeks (according to Jeans). The rate of loss falls off very rapidly beyond this, so that, with an average velocity one fifth that of escape, the atmosphere would remain for hundreds of millions of years.

The moon's surface reaches a temperature exceeding 100° C. during every rotation, and it follows that neither air nor water-vapor could permanently remain above its surface. If at any time in its past history, it has been really hot, like molten lava, it could have retained no trace of atmosphere. For Mercury, the escape velocity is half as great again as for the moon; but the planet, being so near the sun, is much hotter, and it, too, can not retain an atmosphere. Mars, with an escape velocity of 5 km/sec, could not hold hydrogen but should retain water-vapor—as it appears to have done—and all heavier gases. Venus and the earth, at their present temperatures, should retain even hydrogen, and the major planets would do so even if incandescent.

This reasoning explains the cases of Mercury and the moon, and leads to the important conclusion that all smaller bodies, such as the asteroids and satellites, must be wholly devoid of atmosphere—except perhaps bodies like Neptune's satellite, which is relatively massive, and must be very cold. We can not be sure about Pluto, for we know neither its size nor its mass; but it is probable that, at most, it may have a thin atmosphere, like Mars.

The same principle was invoked, shortly after its discovery, to explain the great difference in mean density between the major and the terrestrial planets. The moon, Mercury, Mars, Venus and the earth all have densities between 3.3 and 5.5 times that of water. The rest are almost certainly what we know the earth to be, spheroids of rock, with cores of metallic iron of varying sizes. For the major planets, the densities range from 1.6 for Neptune to 0.7 for Saturn. Moulton suggested, about 1900, that they contained great quantities of light substances, which the smaller terrestrial planets had not been able to keep from diffusing away into space. This has been fully confirmed by later studies.

From the ellipticity of a planet and the changes in its satellites' orbits caused by the attraction of its equatorial bulge, information may be obtained regarding the degree to which the density increases toward its center. Applying this to Jupiter and Saturn, Jeffreys concludes that they contain cores of rock and metal, like the inner planets, surrounded by vast shells of ice—frozen oceans thousands of miles deep—and above this, again, atmospheres of great extent. Throughout most of the atmospheres, the pressure must be so great that the gas is reduced to a density as great as it would have if liquefied, or even solidified, by cooling. Indeed, Wildt believes that the enormous pressure would actually solidify even the "permanent" gases.

Now this outer layer is of low density—less than 0.78 for Jupiter and 0.41 for Saturn—according to Wildt's calculations. This excludes all but a few possible constituents. Frozen oxygen has a density of 1.45, nitrogen 1.02, ammonia 0.82. Only hydrocarbons (methane 0.42, ethane 0.55), helium (0.19) and hydrogen (0.08) come within the limits even for Jupiter. We can therefore conclude, from considerations of density alone, that the outer parts of Jupiter probably, and of Saturn certainly, contain great quantities of free hydrogen or helium. Uranus and Neptune are similar to Jupiter.

It is generally believed that the planets have been produced, in some way or other, from matter ejected or removed from the sun. No really satisfactory theory of the process of formation has yet been devised; but no other hypothesis has yet done better, and the isolation of the sun and planets in space makes a common origin highly probable.

Now we know the composition of the sun—at least of its outer layers—much better than we do that of the planets. Quantitative spectroscopic analysis, though still beset with difficulties, has advanced far enough to show that most of the sun's outer layers is composed of hydrogen; next come helium, oxygen and carbon, followed by nitrogen, then silicon and the metals. A mass of matter removed from the sun and allowed to cool without serious loss would therefore closely resemble the major planets. If small enough to lose all its atmosphere, it would be like the moon or the asteroids—though there are difficulties in seeing how such small masses could have escaped diffusing away altogether before the more refractory constituents solidified.

The history of a body of intermediate mass is more interesting. Hydrogen and helium would be lost while it was still very hot. So would most of the other light gases such as neon and nitrogen (which at the temperature even of the sun's surface is dissociated into atoms). Free oxygen, too, would escape, but a good deal might be retained in combination with silicon and the metals. As the gaseous mass cooled, by expansion and radiation, drops of molten metal and lava would form within it, as Jeffreys suggests, and fall toward the center, building up a molten core. After the first turbulence was over, there would remain a molten planet surrounded by an atmosphere containing heavy inert gases, such as argon, perhaps some carbon dioxide, and as much of the nitrogen and neon as had failed to escape. Menzel and I, a few years ago, noticed that neon, while apparently fully as abundant in the stars and nebulae as argon, is but 1/500 as abundant in the earth's atmosphere; while nitrogen, which is cosmically an abundant element, showing strong spectral lines, forms but a very small portion of the earth's mass. It appears, therefore, that a mass of the earth's magnitude must have lost almost, though not quite, the whole of its primitive atmosphere.

Still following Jeffreys, it appears that, as the molten earth cooled, the two-thousand-mile deep sea of lava solidified first at the bottom (where the melting point was greatly raised by pressure) and so gradually to the surface. During this process great quantities of gases, mainly water-vapor, must have been evolved from the solidifying magma, and escaped to the surface, forming a new atmosphere which now would not escape, since the surface was cooler. With solidification would come rapid superficial cooling, and an ocean would bathe the rocky crust, leaving an atmosphere of moderate extent. Carbon dioxide—evolved from the magma, and perhaps partly primitive—would be a major constituent, along with nitrogen, argon, neon and other minor left-overs. The presence of free oxygen seems very unlikely, for practically all volcanic rocks and gases are unsaturated with respect to this element—the former containing much ferrous iron and the latter being often actually combustible when they meet the air.

The present rich supply of oxygen appears to be a by-product of terrestrial life. (This suggestion is more than a century old.) The earth, indeed, may be regarded as an intensively vegetated planet, from whose atmosphere the greedy plants extract the remaining residue of carbon dioxide so rapidly that if it were not returned to the air by combustion, respiration and decay, the whole supply would be exhausted in a decade or so. Oxygen removed from the atmosphere by these processes is speedily returned by plants; but there is another process of slow depletion which is irreversible. During rock-weathering, about half the ferrous iron of the rocks is oxidized to the ferric state. Goldschmidt (from whose admirable geochemical papers the present discussion is borrowed) concludes that the amount of "fossil" oxygen thus buried in the sedimentary rocks is at least as great as that now present in the atmosphere and may be twice as great. An amount of carbonaceous or other organically reduced material equivalent to both the free and the fossil oxygen must also be in the sediments—which is not unreasonable. Given time enough, this inexorable process of rock-decay might exhaust the remaining oxygen of our atmosphere and put an end to all that breathes. But this danger is indefinitely remote—a billion years away anyhow, since life has lasted that long and only half the oxygen has been used up; and probably much longer, for volcanic gases are still carrying "juvenile" carbon dioxide into the air that has never been there before.

It is of no small interest, however, to look at Mars and see there what looks very like the end of this process. The reddish color of the planet—unique among the heavenly bodies—is just what might be expected, and indeed is almost inevitable in a surface stained with ferric compounds. (The unoxidized rocks of the moon are gray or, at most, brownish.) Wildt suggests that, in the thin atmosphere of Mars, the ozonized layer produced by the action of ultraviolet light at the top of the atmosphere should be near the surface—not high up, as it is here—and that oxidation processes at the planet's surface might thus be accelerated.

It would be premature, however, to conclude that Mars must be a lifeless planet. The depletion of oxygen would be very slow, and plant life would probably adjust itself, as it has done on the earth in response to far more rapid climatic changes. Whether animal life, if ever present, could have survived, is speculation. A race of no more intelligence and engineering skill than our own could presumably meet the situation and survive in diminished numbers breathing electrolytic oxygen—provided that it paid any attention to changes so slow as to be imperceptible in a thousand generations!

While Mars resembles the final stage of our suggested process, Venus seems to be at the beginning, and much like what a lifeless earth would be. We do not know how life began here, but conditions may well have been much less favorable on Venus. Wildt concludes that the powerful "blanketing" effect of the atmospheric CO_2, combined with the stronger solar radiation, may raise the temperature at the planet's actual surface to 100° C. or higher—in which case the failure of life to develop is not surprising. The real puzzle is the apparent absence of water on Venus' surface. She is almost a twin of the earth in size, mass, density, and so on, and one might have expected an ocean of comparable volume. Wildt suggests that all the water has gone into hydrated minerals; but how this could happen unless there was much less there originally than on earth is hard to understand.

For the major planets we have to consider the course of events in a cooling mass containing an excess of the lighter elements and especially of hydrogen. The condensation of the refractory constituents should take place much as for a smaller body. The principal constituents of the rocks, however—potassium, sodium, magnesium, aluminium, calcium and silicon—are not reduced from their oxides by hydrogen, and would form rocks not unlike those of the earth. But at high temperatures the oxides of iron are reduced by hydrogen. My colleague, Professor H. S. Taylor—to whom I am greatly indebted for counsel on these problems of physical chemistry—remarks that the drops of molten lava falling through a hydrogen atmosphere reproduce pretty closely the conditions of a blast furnace. We may conclude then that most of the iron would go into the core and less into the rocky shell.

After the core solidifies, the remainder of the mass will remain fluid over a wide range of temperature. Its principal elementary constituents will be hydrogen, helium, oxygen, carbon and nitrogen, with smaller quantities of the other inert gases, sulfur and the halogens.

The principal reactions which occur in such a gaseous medium at different temperatures and pressures have been carefully studied, for, in addition to their theoretical interest, they are of great practical importance in chemical industry.

When oxygen, carbon and hydrogen are considered the main reaction is

$$CO_2 + 4H_2 \leftrightharpoons CH_4 + 2H_2O$$

The formation of methane is accompanied by diminution of volume: hence it will be favored by high pressure. High temperature works the other way: from the free-energy data it appears that, at 1000° C. and atmospheric pressure, the equilibrium inclines to the side of carbon dioxide, even in the presence of a large excess of hydrogen. Below 300° C. practically all the carbon should go into methane: at about 600° the amounts of the two gases should be comparable.

With hydrogen and higher hydrocarbons the tendency of the reaction is always towards methane at low temperatures. With saturated hydrocarbons, this involves no change of volume and should not be affected by pressure. Formation of methane from unsaturated hydrocarbons should be favored by high pressure. The exclusive presence of methane in the planets' atmospheres might thus have been predicted.

The formation of ammonia from its elements, in accordance with the equation

$$N_2 + 3H_2 \rightleftarrows 2NH_3$$

liberates less energy. With excess of hydrogen, and at atmospheric pressure, the amounts of nitrogen and ammonia should be equal between 200° and 300° C.; ammonia should predominate at lower temperatures and at higher pressures.

The oxides of nitrogen are endothermic and so would tend to dissociate, rather than to form.

We may now form a definite picture of the successive reactions which will occur in the atmosphere of a cooling major planet. At temperatures of about 1000° the predominant hydrogen will be mixed with steam, free nitrogen and carbon dioxide—the carbon monoxide which occurs in stellar atmospheres having long ago been completely oxidized. With falling temperature the carbon dioxide will be converted into methane before the water reaches its critical temperature and begins to condense. After most of it has been precipitated, the nitrogen will go over into ammonia. These reactions, however, will run their course at these relatively low temperatures only with appropriate activation. For the formation of methane an excellent catalyst is available in the partially reduced oxides of iron which should be present on the rocky surface exposed to hot hydrogen. These would be equally good for the ammonia, but they may be at the bottom of the sea by the time the proper temperature is reached. An adequate activation, however, would be furnished by electrical discharges—and, if terrestrial thunderstorms are any guide, these should be abundant so long as vapors arising from the hot ocean are being condensed. When the temperature has fallen to that which the earth at present enjoys, there will be an extensive atmosphere of hydrogen, mixed with the simple hydrides—methane, ammonia and water-vapor, along with any inert gases which may all along have been present, but with little or no free nitrogen or carbon dioxide. Below this will be an ocean—perhaps very deep, strongly alkaline with ammonia, and incidentally containing in solution any compounds of sulfur and the halogens which may originally have been present. The conditions in such an alkaline ocean—its action on the rocky bed, the compounds which it will hold in solution, and the deposits which it may form—would be of great interest, but are outside our present scope.

With further cooling the water will freeze, but at a temperature below 0° C. depending on the percentage of ammonia. With one part of the latter to two of water the freezing point would drop to −100° C., but it is doubtful if there is enough ammonia for this. The major planets—even Jupiter—are still colder, and the water must be thoroughly frozen out of their atmospheres, leaving only ammonia and methane. The ammonia, indeed, must be at the point of precipitation. Dunham has obtained in this way a minimum temperature for Jupiter's visible surface. The ten meters of ammonia above the surface, under the planet's surface gravity, should exert a pressure of 1.5 mm (on the familiar laboratory scale). The vapor tension of the solid (below the triple point) has this value at −107° C. At a lower temperature the observed quantity of ammonia could not exist in the atmosphere—it would partially condense itself by its own weight.

If the atmosphere consists mainly of hydrogen this limit may be lower, for the mean molecular weight is diminished, and the partial pressure of the ammonia in the same proportion. With a large excess of hydrogen the pressure may be reduced to one sixth of the previous value and the limiting temperature to −120° C.

The direct radiometric observations of Jupiter indicate a temperature of about −135°; but this determination is complicated by large and rather uncertain corrections for the absorption of infra-red radiation in the atmospheres of the earth and the planet, so that the agreement is about as good as could be expected. It is, therefore, very probable that the clouds which form Jupiter's surface are composed of minute crystals of frozen ammonia. A perfectly absorbing and radiating planet, at Jupiter's distance and heated exclusively by the sun, would have a mean temperature of −151° C. The excess in the actual temperature may be attributed partly to the fact that we observe the sunlit (and warmer) side; partly to the "greenhouse" effect of the atmosphere, which lets in the short-wave radiation from the sun much more easily than it lets the long-waves emitted from the planet's surface out again; and partly, perhaps, to some residual internal heat in the planet. The existence of the latter is made probable by the rapid changes in the cloud-forms, which often suggest the ascent of new material from below. The variety of colors upon the surface, which range from clear white through pinks and browns almost to black, remain unexplained.

On Saturn, where the ammonia bands are fainter than on Jupiter and the surface gravity less than half as great, the limiting temperature may be 10° or 15° lower. The radiometric observations indicate about the same difference.

Uranus and Neptune, being farther from the sun, should be still colder. The ammonia should be frozen out of their atmospheres, leaving them clear to a greater depth, which may explain the extraordinary strength of the methane bands in their spectra. The methane itself must be nearly ready to condense on Neptune, despite its very low boiling point. Assuming, roughly, that Neptune has six mile-atmospheres of methane above its surface, the pressure, due to this alone, would be about 500 mm and the limiting temperature −165° C. A large excess of hydrogen might reduce this to −183°. Solar radiation alone would maintain a mean temperature near −220°. Whether the difference arises from the powerful "greenhouse" effect of the methane itself, or from internal heat, can not yet be determined. It may be, however, that if the methane could once be frozen out of Neptune's atmosphere, the surface temperature would fall so much that it would stay frozen and leave the planet with an atmosphere which, apart from the inevitable Rayleigh scattering, exerted no influence upon visible light.

The problem of planetary atmospheres, so perplexing a few years ago, is now far advanced toward its solution. Toward its interpretation many of the sciences have contributed—astronomy, physics, chemistry, geology, biology and technology. No one of them alone could have resolved the difficulties. It may, therefore, be appropriate that the attention of so general a scientific gathering may have been invited for a while to it: for it truly illustrates the old motto, "In union there is strength."

SCIENTIFIC EVENTS

THE BRITISH WATER POLLUTION RESEARCH BOARD

IN the annual report of the Water Pollution Research Board for the year ended June 30, 1934, issued by the Department of Scientific and Industrial Research, according to a summary in the London *Times*, reference is made to the exceptional conditions of weather during 1933 and 1934. The long spell of dry weather not only caused difficulties in the provision of ample quantities of water, but also had a serious detrimental effect on the quality of the water in rivers and streams into which sewage and trade effluents are discharged, as less water than usual was available for dilution of the discharges.

The investigations initiated by the board may be divided into four main groups dealing respectively with purification of water for public supply, methods of treatment and disposal of sewage, methods of treatment and disposal of trade effluents, and various problems of river pollution.

With regard to water for public supply, many experiments have been carried out with the object of ascertaining the effects of various factors on the treatment of water by the base-exchange process of softening. During the last two years experiments have been carried out on methods of treatment of British clays with the object of preparing base-exchange material suitable for water softening. Many samples of clays have been employed and a method of treatment has been devised whereby prepared clays have been produced with water-softening capacities greater than those of some imported materials at present in use.

Further experiments have been carried out in the laboratory on methods of treatment of the waste waters discharged from dairies and milk products factories. These effluents may seriously affect rivers and streams into which they are discharged, and may be many times as strong in polluting character as domestic sewage. The problem is of particular importance at the present time because of the expansion of the milk industry and the increase in the number of large centralized factories and milk collecting and distributing depôts. During the year many cases of serious difficulty and pollution of streams by such effluents have arisen. The experiments have indicated that there are methods whereby the effluent can be satisfactorily purified before disposal, and a stage has been reached at which the processes suggested should be tested on a large scale. The industry has been informed of the progress of the work and has been offered the opportunity of cooperating both technically and financially in the further investigations which are desirable.

Considerable progress has been made in fundamental investigations of the biology and chemistry of methods of purification of sewage.

The question has also arisen whether the amount