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Spectra of the Planets

N. T. Bobrovnikoff
Perkins Observatory, Ohio Wesleyan University and Ohio State University, Delaware, Ohio

INTRODUCTION

THE solar system consists of the central self-luminous body, the sun, and a large number of intrinsically dark smaller bodies revolving around it. These include, first, all planets which can be divided into two classes according to their diameters and mean densities. The first group consists of terrestrial planets: Mercury, Venus, the Earth, Mars, and probably Pluto. They are characterized by small dimensions and high mean density. The second group consists of major planets: Jupiter, Saturn, Uranus, and Neptune. They are all large in comparison with the earth, and have a low mean density.

In addition to the nine planets and their satellites, many thousands of asteroids, or minor planets, move around the sun between the orbits of Mars and Jupiter. They represent the link between the smallest planets like Mercury, through satellites, to the smallest fragments of rock and iron which we call meteors. Aggregations of meteors, molecules, and atoms form the zodiacal light and comets, and contribute to the permanent luminosity of the night sky.

We have here in our solar system a grand scale of nature from the largest mass of gas to the smallest individual atom, and this scale is repeated in every corner of the universe to which our telescope can penetrate.[1] The exact relationship of all these bodies is far from being understood, and at the present time even the origin of the planets is as much of a puzzle as it has ever been.

The present paper deals with the spectra of the planets, but it should be realized at the outset that spectroscopy does not supply us with complete information about the planets. An observer on Mars having at his disposal our best spectroscopic equipment would find no evidence of free nitrogen in the absorption spectrum of our atmosphere. If on the basis of this information he were to construct a model of our atmosphere, we would hardly recognize it.

Our knowledge of physical conditions on the planets is based on a large number of facts obtained by different methods of observation. Some of these facts can be fitted into a consistent scheme, while others at the present time cannot be reconciled with the main body of our knowledge.

Besides the general information from the theory of gravitation about the mass, mean density, etc. of the planets, the following methods of observation are at our disposal:

(a) *Total brightness.* By this is usually meant the brightness of the planet in the visual region of the spectrum, referred to the mean distance of the planet with the elimination of the effect of phase-angle. Periodic variations in the light of many asteroids can be easily explained by the irregularity of their surface. However, a recent discussion[2] of observations of the brightness of planets resulted in the establishment of long-period variations for Mars, Jupiter, Saturn, Uranus, and Neptune. On the basis of spectroscopic data we think that in major planets we do not see the solid surface. The sunlight is reflected from a level determined by the abundance of ammonia crystals. This factor depends on a photochemical reaction and may conceivably be expected to follow the sun-spot curve with a period of 11.1 years. Instead of this we have for the periods in the variation in light:

Jupiter	11.6±0.4 years
Uranus	8.4±0.3 years
Neptune	21.0±0.6 years

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[1] Direct observational evidence for the universe at large is restricted to self-luminous bodies, that is, stars, and cosmic clouds of meteors, dust, molecules, and atoms. The existence of intermediate bodies, such as planets, outside our own system, cannot be proved at the present time. Recent results of gravitational analysis of the motion of certain double stars strongly indicate that bodies of the size of ten to fifteen times the size of Jupiter do exist. This conclusion must be accepted with caution, as it is based on the interpretation of such minute departures from the motion of double stars predicted by gravitation, that systematic errors of observation may vitiate the result.

[2] W. Becker, Preuss. Akad. Wiss. **28**, 839 (1933).

(b) *Direct visual observation.* In the case of the planet Mars this approach resulted in a wealth of controversial data. Nobody can doubt, however, that we do see the solid surface of Mars with its innumerable markings. It is quite otherwise with Venus and the major planets. In spite of the fact that we observe only their atmospheres, formations in these atmospheres are strangely stable in comparison with terrestrial clouds. The Great Red Spot on Jupiter has been under observation for certainly over a century and perhaps even for three centuries, and it still does not show any tendency to dissolve. Uranus shows fluctuations in light with a period corresponding to the exact period of rotation. Neptune shows similar fluctuations with a period exactly one-half the period of rotation. This implies the existence of conspicuous and semi-permanent configurations of clouds on one side of Uranus. For Neptune we must assume two such configurations exactly opposite each other. In neither planet can we observe the details of the surface directly, owing to their small apparent diameters.

(c) *Polariscopic observations.* Recently[3] a considerable amount of observational evidence for the polarization of light by planets became available. The detailed results of such observations indicate extreme complexity of the atmospheres of the planets. In 1923 there was found, for instance, a marked difference in the amount of polarization between the northern and southern limb of Jupiter. In 1926 this difference disappeared but the west limb was more polarized than the east limb.

(d) *Radiometric observations.* These consist in the separation by means of filters of the reflected radiation of the sun from the longer wave-length radiation (planetary heat) absorbed by planetary atmospheres or surfaces and re-emitted in the far infra-red part of the spectrum. This method gives considerable information about the temperature and its variations at different points of the surface of the moon and Mars. For the major planets the situation is complicated by the heavy bands of methane undoubtedly present in the far infra-red. The maximum of their infra-red spectrum is at much longer wave-lengths than for the nearer planets, and this fact together with the low intensity of their radiation makes the measurement of the planetary heat somewhat uncertain. Generally speaking, their temperatures measured by means of a thermocouple are very close to those of rapidly rotating black bodies at their respective distances from the sun.

(e) *Occultation and eclipse phenomena.* Occultations of stars and satellites provides valuable information about the presence and structure of the atmospheres of the planets. Data on the refraction and density gradient of the atmosphere can be obtained in this way. The progress of eclipses of satellites in the system of Jupiter can be interpreted[4] as showing the existence of an absorbing layer above the visible surface of the planet. Such an interpretation is very difficult to reconcile with the model of Jupiter's atmosphere derived from spectroscopic observations.

(f) *Color-indices and filter photography.* This method may be described as crude spectroscopy inasmuch as definite regions of the spectrum are isolated. The total brightness within those regions is compared for color-index, or the details of structure of various formations are studied. As color-indices (the difference between the photographic and visual magnitude) of very faint bodies, such as asteroids, can be determined while their spectra are unobtainable, this method supplies important information on the physical properties of smaller bodies in the solar system.

(g) *Spectroscopy of the planets* forms the subject of the present report. The limitations of spectroscopy are twofold. The ultraviolet part of the spectrum of all celestial bodies is cut off by the ozone band in the atmosphere of the earth at about $\lambda2900$A. On the other hand the extension to the infra-red part of the spectrum is difficult on account of the faintness of the surfaces of planets. At the present time the limits in the infra-red are at about $\lambda10{,}000$A for Venus, Jupiter, and Saturn, and at about $\lambda7200$A for Uranus and Neptune.

It is obvious that spectroscopic data on the planets should be interpreted in conjunction with the data obtained by other methods. However, such an attempt cannot be done in a short paper.

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[3] B. Lyot, Ann. Obs. Paris Meud. **8**, 1 (1929).

[4] D. J. Eropkin, Zeits. f. Astrophys. **3**, 163 (1931); F. Link, Bull. Astron. [2] **9**, 227 (1933).

Therefore other data than spectroscopic will not be considered here unless they are of especial interest and significance.

In the spectroscopy of the planets the main source of information is absorption bands produced by their atmospheres in the reflected spectrum of the sun. The continuous background of the spectrum is also of importance for the study of the selective reflection of their surfaces or atmospheres. No emission lines have ever been photographed in the spectra of the planets contrary to older observations made visually.

Even before absorption bands in some planets were identified, spectroscopy had made an important contribution to the physics of the planets. If we set the slit of the spectrograph along the equator of the planet, the lines in the reflected spectrum of the sun will generally be inclined. This is due to the Doppler effect as the rotation of the planet will make one limb approach the observer, and the other recede. The rotation period of the planet can be determined in this way. In fact for Uranus and Neptune only periods so derived are available. The spectroscopic method was also used to prove that the rings of Saturn consist of swarms of small bodies obeying Kepler's laws of motion.

In discussing the absorption spectra of the planets we shall deal with the rotation-vibrational spectra of polyatomic molecules CO_2, (Venus) NH_3, and CH_4 (the major planets). The purely rotational spectra of these molecules must also be present, but they cannot be detected with our present means of observation.

MERCURY AND PLUTO

Mercury, the nearest to the sun, and Pluto, the farthest known planet in the solar system, appear to have much in common in regard to their size, mass, and absence of an atmosphere. For both planets we have direct observational evidence[5] that their spectrum is a purely reflected spectrum of the sun without any noticeable modification.

VENUS

For a long time Venus has been known to possess an extensive atmosphere, but it was only in 1932 that three absorption bands were observed[6] in the infra-red part of its spectrum and identified as belonging to carbon dioxide.

The CO_2 molecule possesses[7] three fundamental frequencies

$$\begin{array}{ll} \nu_1 & 1321.7\ \text{cm}^{-1} \\ \nu_2 & 667.9 \\ \nu_3 & 2362.8 \end{array}$$

of which ν_1 is inactive in the infra-red. As $2\nu_2$ is approximately equal to ν_1, resonance phenomena are introduced with considerable complications in the spectrum. The Venus bands are all of the parallel type with the *Q*-branch missing. The convergence of the rotational lines in the *R*-branch depends on the moment of inertia of the molecule. In the case of the CO_2 bands in Venus the convergence is so strong that the bands appear very much like those of diatomic molecules.[8]

On the basis of the moment of inertia required to produce the observed convergence of the rotational lines Adams and Dunham identified the molecule as CO_2. Adel and Dennison[9] showed that the bands observed in Venus should be classified as in Table I.

TABLE I. Carbon dioxide bands in Venus.

λ	Designation
8689A	$5\nu_3$
7883	$5\nu_3+\nu_1$
7820	$5\nu_3+2\nu_2$

It is fair to notice here that the presence of carbon dioxide in the atmosphere of Venus was partially anticipated by E. Schoenberg.[10] On the

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[5] Mercury: W. S. Adams and T. Dunham, Pub. Astronom. Soc. Pac. **44**, 380 (1932). Pluto: M. L. Humason, Carnegie Inst. of Wash. Year Book **40**, 13 (1941). According to G. P. Kuiper, Astrophys. J. **100**, 378 (1944), the question of the spectrum of Pluto cannot be considered as closed.

[6] W. S. Adams and T. Dunham, Pub. Astronom. Soc. Pac. **44**, 243 (1932).

[7] Ta-You Wu, *Vibrational Spectra and Structure of Polyatomic Molecules* (The China Science Corporation, Shanghai, 1939), p. 144.

[8] For a reproduction of the band λ7820A showing the rotational structure see T. Dunham, Pub. Astronom. Soc. Pac. **51**, 253 (1939).

[9] A. Adel and D. M. Dennison, Phys. Rev. **43**, 716 (1933); **44**, 99 (1933).

[10] "Untersuchungen über die Atmosphäre der Planeten Venus," Sitzb. Preuss. Akad. Wiss. **21**, 383 (1931).

basis of the data on the albedo and diffusion of light in the atmosphere of Venus he came to the conclusion that the atmosphere of that planet consists of one-third of carbon dioxide and two-thirds of hydrogen. However, there is no spectroscopic evidence[11] that there is any other gas in the atmosphere of Venus besides carbon dioxide. This does not preclude the possibility of the presence of small amounts of hydrogen and inert gases in the upper part of the atmosphere. Wildt[12] looked for electronic bands of formaldehyde, CH_2O, in the near ultraviolet. Formaldehyde should be formed in the atmosphere of Venus by photosynthesis if there is any water-vapor present. His spectrograms failed to reveal any such bands.

Carbon dioxide in the atmosphere of the earth produces absorption bands in the infra-red, especially the double band designated ω_1 and ω_2 at about 2μ, and bands at 4.3μ and 15.0μ. These are the simpler harmonics of the CO_2 molecule. The bands observed in Venus have not been detected in the solar spectrum at sunset when the amount of carbon dioxide in the path corresponds to 30 meters of gas at atmospheric pressure. Obviously the amount of carbon dioxide in the atmosphere of Venus must be very large. The equivalent path in carbon dioxide was estimated by Adel[13] to be at least 100 meters at atmospheric pressure, but Dunham's experiments indicate that a path of even 400 m-atmos. is not sufficient to reproduce the Venus bands with the observed intensity.

The atmosphere of Venus is laden with clouds especially well seen on the ultraviolet photographs. The nature of these clouds is unknown. Polarimetric observations and considerations based on the reflection of light by the planet strongly indicate that these clouds must consist of solid particles of a rather large size. Frozen carbon dioxide is impossible in view of the high temperature[14] on Venus. Wildt[12] made the suggestion that particles in clouds are polyoxymethylene hydrates $(CH_2O)_x \cdot H_2O$ but later withdrew[15] this hypothesis.

THE EARTH

The spectrum and composition of the earth's atmosphere is of great interest not only to astronomers but also to meteorologists, geophysicists, etc. The very extensive literature on this subject cannot be reviewed here even briefly. We have to deal not only with the absorption spectra of molecules produced by the filtering of sun-light through the atmosphere of the earth, but also with emission spectra of atoms and molecules produced by the ultraviolet light of the sun or perhaps by corpuscular bombardment and observable in aurora polaris, and in the permanent aurora of the night sky. Other cosmic agencies, such as lightning, also supply in their spectra some information about the constitution of our atmosphere.

At the present time bands of the following molecules have been found[16] in the solar spectrum as modified by the absorption in the atmosphere of the earth: O_2, O_3, H_2O, HDO, N_2O, N_2O_5, and CO_2.

Of more immediate interest to the spectroscopist are atmospheric lines in the region of the solar spectrum that can be photographed, that is from about λ3000A to λ11,000A. In the spectrum of a planet such as Jupiter we see not one but three spectra superimposed on each other: the spectrum of the sun reflected by Jupiter, absorption bands produced in the atmosphere of Jupiter, and telluric absorption bands produced by the atmosphere of the earth. To unravel this combination of spectra is by no means an easy matter with the small dispersion generally employed in planetary spectroscopy. In the region λ7600A to λ10,000, out of 3297 absorption lines measured in

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[11] V. M. Slipher, Monthly Not. R.A.S. **93**, 657 (1933); C. St. John and S. B. Nicholson, Astrophys. J. **56**, 380 (1922).

[12] R. Wildt, Astrophys. J. 92, 247 (1940). The same negative result was obtained by Adams and Dunham, Carnegie Inst. of Wash. Year Book **40**, 13 (1941).

[13] A. Adel, Astrophys. J. **85**, 345 (1937).

[14] A. Adel's estimate (Astrophys. J. **86**, 337 (1937) is greater than 50°C in good agreement with previous radiometric measures. However, E. Pettit and S. B. Nicholson, Science **72**, 407 (1930), give for the temperature of the visible layer of the atmosphere of Venus −31°C with very little difference in temperature of the illuminated and dark side of the planet. R. Wildt, Astrophys. J. **91**, 266 (1940), comes to the conclusion that the temperature of the sub-solar point on the surface of Venus is higher than the boiling point of water. The rise of temperature is due to the action of carbon dioxide.

[15] R. Wildt, Astrophys. J. **96**, 312 (1942).

[16] A. Adel and C. O. Lampland, Astrophys. J. **87**, 198 (1938); A. Adel, Astrophys. J. **93**, 509 (1941).

Table II. Telluric bands.

Band	λ	Molecule	Designation
Φ	11,358A	H_2O	$\nu_1+\nu_2+\nu_3$
ρ	9420	H_2O	$2\nu_1+\nu_3$
Y	9062	H_2O	$3\nu_3$
Z	8227	H_2O	$2\nu_1+\nu_2+\nu_3$
	7957	H_2O	$\nu_2+3\nu_3$
A	7594	O_2	$A^1\Sigma-X^3\Sigma(0,0)$
a	7228	H_2O	$3\nu_1+\nu_3$
	6982	H_2O	$\nu_1+3\nu_3$
B	6867	O_2	$A^1\Sigma-X^3\Sigma(1,0)$
	6514	H_2O	$3\nu_1+\nu_2+\nu_3$
	6315	H_2O	$\nu_1+\nu_2+3\nu_3$
α	6277	O_2	$A^1\Sigma-X^3\Sigma(2,0)$
	5943	H_2O	$3\nu_1+2\nu_2+\nu_3$
	5916	H_2O	$4\nu_1+\nu_3$
δ	5789	O_2	$A^1\Sigma-X^3\Sigma(3,0)$
	5714	H_2O	$2\nu_1+3\nu_3$

the solar spectrum, no fewer than 837 lines have been found to belong to water vapor and 124 to the oxygen molecule.[17] Generally speaking, lines of solar or planetary origin can be identified by their Doppler shift in respect to the telluric lines.

The telluric bands in the near infra-red and visible part of the spectrum are given in Table II:

The wave-lengths are given for the zero rotational energy of the H_2O molecule, and for the *R*-heads of the O_2 molecules. The convenient notation given in the first column is unfortunately not universally accepted, older authors using some of the letters of Table II for different bands.[18]

The oxygen electronic band *A* is the most conspicuous feature in the near infra-red on every stellar spectrogram. It has made an important contribution to physics as in this band oxygen isotopes 17 and 18 were discovered.

MARS

The atmosphere of Mars is of especial interest in view of popular speculations about the possibility of life on that planet. However, with the increasing precision of observation less and less either of oxygen or of water is being detected on Mars.

In 1908 Very[19] estimated from the study of the *a*-band (Table II) that the atmosphere of Mars contained 1.75 times as much water-vapor as above Flagstaff during the observation. The *B*-band of oxygen was found by him to be 15 percent stronger in the spectrum of Mars as compared with the moon.

Adams and St. John[20] studying the same bands in 1925 found that the quantity of water-vapor in the atmosphere of Mars was 3 percent of that over Pasadena, and the quantity of oxygen two-thirds of that over Mount Everest.

In 1933 Adams and Dunham[21] came to the conclusion from the study of the *B*-band that the amount of oxygen in the atmosphere on Mars was less than one-tenth of one percent of that over an equal area of the earth. Equally decisive were the results obtained by Adams[22] in 1943. No trace of oxygen, water-vapor, or carbon dioxide was found in the spectrum of Mars. An estimate of the maximum quantity of water-vapor and oxygen in the atmosphere of Mars as one percent of that in the atmosphere of the Earth would appear liberal.

These results are hard to reconcile with the well established results obtained by other methods. Such are: visual observations of clouds on Mars, seasonal changes in the shape and color of markings on its surface, large and sudden changes in the amount of polarization at different points on the surface of the planet and the aspect of the planet photographed in different colors. As is well known ultraviolet photographs show few details as contrasted with infra-red photographs. This is generally explained by the scattering of light in the atmosphere of Mars analogous to that in the terrestrial atmosphere, where the amount of scattering, in accordance with Rayleigh's formula, is inversely proportional to the fourth power of the wave-length. The nature of the atmosphere of Mars still remains a mystery.

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[17] W. Baumann and R. Mecke, *Das ultrarote Sonnespektrum* (Johann Ambrosius Barth, Leipzig, 1934).

[18] For details see F. J. M. Stratton, *Astronomical Physics* (Methuen and Company, London, 1925), p. 184. The notation of Table 2 up to Frauhofer band *A* is also used in the *Revised Rowland* (Carnegie Institution of Washington, 1928).

[19] F. Very, Lowell Obs. Bull. **1**, 207 and 221 (1909).

[20] Astrophys. J. **63**, 133 (1926).

[21] W. S. Adams and T. Dunham, Astrophys. J. **79**, 308 (1934).

[22] Reported at the Cleveland Meeting of the American Association for the Advancement of Science, Sept. 15, 1944.

ASTEROIDS

The belt of asteroids, or minor planets, occupies with a few exceptions, the space between Mars and Jupiter. In 1938 orbits were known for 1433 asteroids. In addition to these 3311 asteroids have been discovered but the observational data are not sufficient for the computation of their orbits.[23] The total number of asteroids must be very large. The most recent estimate[24] of the number of asteroids bright enough to be photographed with the Mount Wilson 100-inch reflector is of the order of 30,000 to 40,000. Since the largest asteroid, Ceres, has a diameter of only 770 kilometers we have to deal with bodies devoid of atmospheres. Their spectra therefore should be like that of the sun with a possible difference in the distribution of intensity in the continuous background.

Spectra of twelve of the brighter asteroids were observed by the author.[25] In the photographic region they showed a purely solar spectrum which bespeaks a simple reflection of the light of the sun from their surfaces without any modification in their atmospheres. However, the distribution of intensity in the continuous spectrum is often quite different from that of the sun, many asteroids showing a very weak continuous spectrum in the near ultraviolet. A more recent investigation by Deutsch[26] of the spectrum of Vesta is in agreement with these results.

In the visible region up to λ7000 the continuous spectra of Vesta and Ceres are strikingly different from each other as well as from the sun.[25] No indication of the existence of absorption bands at λ5770 and λ5180 suspected by H. C. Vogel[27] in the spectrum of Vesta has been found.

These results can be interpreted as due to the difference in the reflective power of asteroids depending on the wave-length. An investigation of color-indices of thirty-six asteroids by Recht[28] showed not only a variation of color from asteroid to asteroid, but also a variation for the same asteroid (such as Urania and Psyche). This latter effect is presumably caused by the rotation of asteroids whereby different portions of an asteroid's surface are presented to the earth. We must assume, therefore, that surface material of many asteroids is not homogeneous.

THE MAJOR PLANETS

The giant planets of the solar system, Jupiter, Saturn, Uranus, and Neptune have much in common. Table III gives some of the data for these planets.

We notice the short period of rotation, the small density, and the high albedo. The rapid rotation results in the formation of belts of clouds parallel to the equator, especially prominent on Jupiter. The small density, which for Saturn is less than that of water, has an important bearing on the structure of the planets. It is probable that the core of Jupiter is of the same density as the earth and only five times larger. The rest of the planet is an immense layer of ice and frozen ammonia. The high albedo (for comparison albedo of the moon is only 0.07) is good evidence of itself that the planets are surrounded with dense atmospheres. That the measured temperature of the planets is somewhat higher than it should be for a blackbody is another indication of extensive atmospheres.

From the early days of astronomical spectroscopy it was known that the major planets show in their spectra strong absorption bands lacking in the spectrum of the sun. Much work was done on photographing these absorption bands and measuring them at the Lowell Observatory. It was not until 1932 that Wildt[29] identified some of

TABLE III. Data for the major planets.*

	a	P	P'	m	D	A	T	T'
Jupiter	5.20	11.86	9.9	317	1.34	0.41	127°K	135°K
Saturn	9.54	29.46	10.2	95	0.71	0.40	90	120
Uranus	19.19	84.02	10.7	15	1.27	0.45	63	<90
Neptune	30.07	164.80	15.8	17	1.58	0.45	51	—

* In this table a = mean distance in astronomical units, that of the earth being unity; P = sidereal period of revolution in years; P' = period of rotation in hours; m = mass in terms of the mass of the earth; D = average density in terms of water; A = geometric albedo or fraction of the visible light of the sun reflected by the planet; T = black body temperature of the rapidly rotating planet; and T' = actually measured temperature of the planet.

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[23] G. Stracke, "Identifizierungsnachweis der Kleinen Planeten," Abhandl. Preuss Akad. Wiss. No. 4 (1938).

[24] W. Baade, Pub. Astronom. Soc. Pac. **46**, 54 (1934).

[25] N. T. Bobrovnikoff, Lick Obs. Bull. **14**, 18 (1929).

[26] A. N. Deutsch, *Pulkovo Obs. Circ.* No. 25 (1939).

[27] H. C. Vogel, *Untersuchungen uber die Spektra der Planeten* (Leipzig, 1874).

[28] A. W. Recht, Astronom. J. **44**, 25 (1934).

[29] R. Wildt, Veroff. Univ.-Sternwarte Göttingen **22** (1932).

the most prominent bands in the spectra of the major planets with ammonia and methane. Further search for the spectra of molecules with the low boiling point such as ethane (C_2H_6), ethylene (C_2H_4), and acetylene (C_2H_2) proved[30] unsuccessful. There is no spectroscopic evidence at the present time that other than NH_3 and CH_4 molecules are present as gases in the atmosphere of the major planets. Of these two gases methane is by far more important. It is common to all the planets in question and its bands are the most conspicuous feature of the spectra of these planets in the infra-red.

Our present knowledge of the spectrum of methane observed in the planets is summarized in Table IV.

The wave-lengths and identifications of the 41 bands in Table IV are derived from the papers by Adel and Slipher.[31] In columns *J*, *S*, *U*, and *N* for the respective planets, an asterisk denotes the presence of the band. Eight bands in the spectrum of Saturn toward the infra-red were added by me as present in my spectrograms. A series of dots for eleven bands in Uranus is based on some spectrograms obtained by the writer. The bands merge into each other to such an extent that it is impossible to identify all of them. However, it is fairly certain they are present in Uranus.

Table IV is limited in the infra-red by the faintness of the planets, and toward the shorter wave-lengths by the absence of higher harmonics in the spectra of Jupiter and Saturn.

TABLE IV. Methane spectrum of major planets.

$\mu\mu$	Designation	*J*	*S*	*U*	*N*
1009	$3\nu_3+\nu_4$	*			
987	$3\nu_3+\nu_2$	*			
980	$8\nu_4$	*			
942	$6\nu_4+\nu_3$	*			
886	$4\nu_3$	*	*	●	
874	$9\nu_4$	*	*	●	
861	$3\nu_3+\nu_1$	*	*	●	
843	$7\nu_4+\nu_3$	*	*	●	
816	$5\nu_3-\nu_2$	*	*	●	
802	$5\nu_3-\nu_4$	*	*	●	
798	$4\nu_3+\nu_4$	*	*	●	
788	$10\nu_4$	*	*	●	
782	$4\nu_3+\nu_2$	*	*	●	
725	$5\nu_3$	*	*	●	
720	$11\nu_4$	*	*	●	
702	$4\nu_3+\nu_1$	*	*	*	*
683	$6\nu_3-\nu_2$			*	*
673	$6\nu_3-\nu_4$			*	*
668	$5\nu_3+\nu_4$	*	*	*	*
662	$12\nu_4$			*	*
656	$5\nu_3+\nu_2$			*	*
643	$10\nu_4+\nu_3$			*	*
619	$6\nu_3$	*	*	*	*
614	$13\nu_4$			*	*
597	$11\nu_4+\nu_3$			*	*
595	$5\nu_3+\nu_1$		*	*	*
584	$7\nu_3-\nu_4$			*	*
576	$6\nu_3+\nu_4$	*	*	*	*
568	$6\nu_3+\nu_2$			*	*
566	$14\nu_4$			*	*
557	$12\nu_4+\nu_3$			*	*
543	$7\nu_3$	*	*	*	*
534	$15\nu_4$				*
523	$13\nu_4+\nu_3$				*
521	$6\nu_3+\nu_1$				*
509	$7\nu_3+\nu_4$			*	*
504	$7\nu_3+\nu_2$				*
502	$16\nu_4$				*
486	$8\nu_3$			*	*
459	$8\nu_3+\nu_4$				*
441	$9\nu_3$				*

The methane molecule has four fundamental frequencies:

ν_1	2915 cm^{-1}
ν_2	1520
ν_3	3020
ν_4	1306

of which ν_3 and ν_4 are active in infra-red absorption. We notice that ν_1 is very close to ν_3 and different combinations of these frequencies may result in a practically identical position of the center of the bands within several angstroms. This is true, for instance, for the bands $2\nu_1+2\nu_3$ and $\nu_1+3\nu_3$, resulting in λ8603. Furthermore, Adel and Slipher's designation of the bands is based on the use of the simple expression for the energy

$$E/h=(v_1+\tfrac{1}{2})\nu_1+(v_2+1)\nu_2+(v_3+\tfrac{3}{2})\nu_3+(v_4+\tfrac{3}{2})\nu_4$$

and the contribution of the second-order terms in respect to the vibrational quantum numbers cannot be neglected in the final classification.[32] It is obvious that the designation of the bands given in Table IV is only provisional pending an investigation of the rotational structure of these bands. The general picture, however, will not be

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[30] A. Adel and V. M. Slipher, Phys. Rev. **46**, 902 (1934).

[31] A. Adel and V. M. Slipher, Phys. Rev. **46**, 240 and 902 (1934); **47**, 651 (1935).

[32] According to Wu (reference 7, p. 225) all terms in Table IV involving $n\nu_3$ should be changed to $(n-1)\nu_1+\nu_3$, but I did not consider this worth while, as calculated and observed frequencies given by Wu differ sometimes very appreciably. For the band $4\nu_1+\nu_3$ ($5\nu_3$ of Table IV) this difference amounts to 26A, and is likely to be larger for higher harmonics.

changed. The occurrence of very high harmonics, such as $16\nu_4$, in planetary spectra is certain. Of especial interest is the occurrence of the difference bands such as $5\nu_3-\nu_2$, in which the lower state of vibration is excited. Needless to say neither the difference bands nor many of the other bands of Table IV have ever been observed in the laboratory.

There is no question that methane, and not some other molecule, is responsible for the strong bands in planetary spectra. The spectrum of methane was obtained by Adel and Slipher using a pressure of 45 atmospheres and a path of 45 meters. In the region from 4500A to 10,000A some twenty rotation-vibrational bands were photographed which duplicate those in the planetary atmospheres. The fact that not all planetary bands have been produced in the laboratory can be interpreted as the evidence of very large quantities of methane in atmospheres of the planets, especially Uranus and Neptune.

The spectrum of Jupiter shows besides methane bands also fairly strong bands of ammonia which are considerably weakened in the spectrum of Saturn and wholly absent in the spectra of Uranus and Neptune.

In the pyramidal molecule of ammonia, NH_3, we have again four fundamental vibrations:

ν_1 3337 cm^{-1}
ν_2 3415
ν_3 933 and 967
ν_4 1628

Again as in the case of methane the first two frequencies are close to each other with the result that the assignment of the centers of bands is rather uncertain. The main band, astronomically speaking, at λ7928 may be $2\nu_1+2\nu_2$ as well as $4\nu_1$. The bands probably present in the spectrum of Jupiter and Saturn are as shown in Table V.

TABLE V. Ammonia spectrum of Jupiter and Saturn.

$\mu\mu$	Designation
990	$\nu_1+2\nu_2$
891	$3\nu_1+\nu_2$
793	$4\nu_1$
643	$5\nu_1$
549	—

Of these only $4\nu_1$ and $5\nu_1$ are not concealed by much stronger methane bands. In the $5\nu_1$ band the author[33] measured 15 unblended ammonia lines and Dunham[34] identified 30 lines. Dunham also measured 39 lines in the $4\nu_1$ band, so that the identification of these bands with ammonia is certain. According to Dunham a path through ammonia of 40 meters under standard conditions resulted in bands stronger than those in Jupiter. The amount of ammonia above the reflecting layer in the atmosphere of Jupiter is estimated to be equivalent to a path of five to ten meters thick at atmospheric pressure.

Figure 1 represents the spectrum of the moon, Saturn, and Jupiter obtained at the Perkins Observatory with a plane grating spectrograph attached to the 69-inch reflector. The original dispersion is about 45A/mm, and the spectrum is in good focus from λ6000A to λ9000A. The plates were Eastman I–N for the moon and Saturn, and IV–N for Jupiter.

The atmospheric bands *Z*, *A*, *a*, and *B* are very prominent in all spectra and are of comparable intensity since the celestial bodies were at about the same altitude. Some solar absorption lines are also prominent. In the spectrum of Saturn both atmospheric bands and solar lines are seen also in the spectrum of the ring which circumstance makes their identification easy, unless they are very faint.

Several methane bands are marked off on the reproduction. They may be easily recognized in the spectrum of Saturn as they are restricted to the planet itself and do not occur in the rings. Especially strong methane bands are at λ7200 and λ7250 (unfortunately overlapped by the water-vapor band *a*), at λ8600 and at λ8800. This latter band is so strong that the spectrum of the planets ends there abruptly, although the spectrum of Saturn's rings can be followed another 200A into the infra-red. On over-exposed spectrograms this band shows a structure similar to other methane bands. The bands just described are somewhat stronger in the spectrum of Saturn than in the spectrum of Jupiter but the difference in intensity is small.

Finally the ammonia band at λ7930 is dis-

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[33] N. T. Bobrovnikoff, Pub. Astronom. Soc. Pac. **45**, 171 (1933).

[34] T. Dunham, Pub. Astronom. Soc. Pac. **45**, 42 and 202 (1933); **46**, 231 (1934).

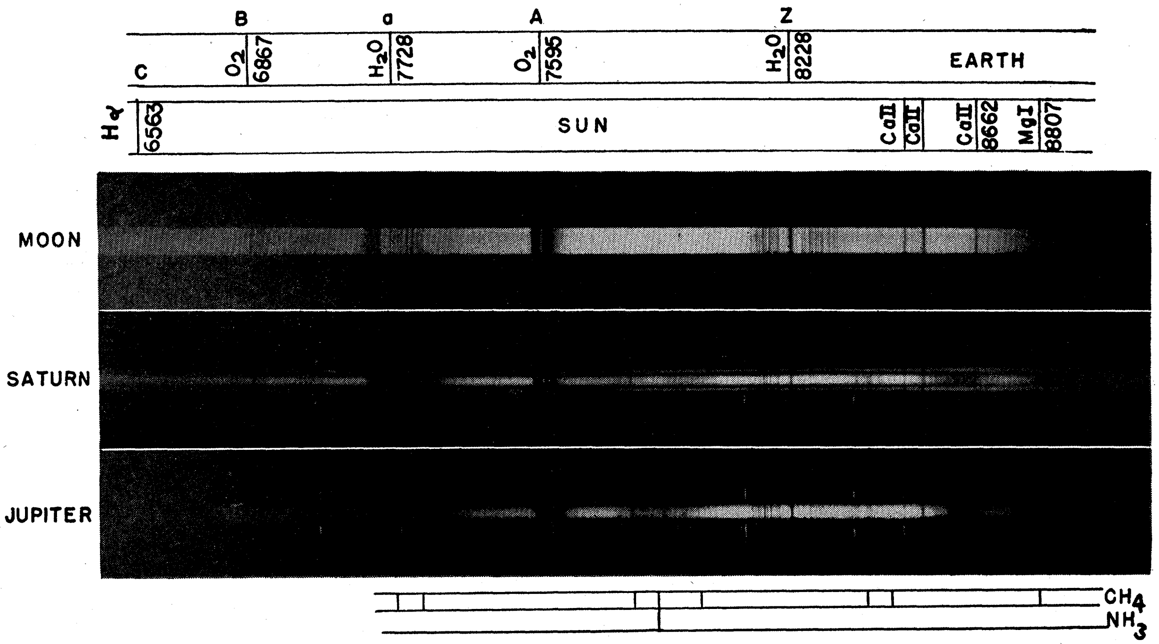

FIG. 1. Spectrum of the moon (upper) (November 1, 1944), of Saturn (center) (November 1, 1944) and of Jupiter (lower) (October 21, 1943). Eastman Kodak emulsion I-N for the moon and Saturn, and IV-N for Jupiter. Solar lines and telluric bands are common to all of these spectra. Some methane and ammonia bands are shown in the spectra of the planets. Note the sudden cut-off of the planetary spectra near λ8800 due to the strong methane absorption. Comparison spectrum neon and argon.

tinctly visible in the spectra of the planets. It is markedly stronger in the spectrum of Jupiter.

We notice that in the distribution of intensity in the continuous spectrum the planets differ from each other as well as from the moon. Jupiter shows a very strong concentration of energy near λ8400, but the maximum of the continuous spectrum of the moon lies toward the shorter wave-lengths, at about λ8000. The continuous spectrum of Saturn is much more uniform with the maximum of intensity at about λ8200. The spectrum of Saturn is more intense than that of Jupiter in the region from λ7200 to the violet, although in the longer wave-lengths the reverse is true.

The continuous spectrum of the rings of Saturn again differs from the planet in the distribution of intensity. It is more like the spectrum of the moon, but it is apparently subject to considerable variations. On some plates the eastern side of the rings can be followed into the infra-red much farther than the western edge. It is known that in the near ultraviolet the spectrum of the rings is much stronger than the spectrum of the planet.[25]

These considerations have a bearing on the composition of the atmosphere of the planets as the continuous spectrum must be produced by scattering of sunlight by some particles in the atmosphere. Since sunlight penetrates to about the same depth in the atmospheres of both planets, as evidenced by the almost equal intensity of methane bands, the scattering process must be quite different in the two cases. As to the agent producing this scattering we have at present no information. The temperatures of the major planets are low enough, and the pressures in their atmospheres are high enough to produce liquid or even solid hydrocarbons, ammonia, indeed hydrogen, and helium. However, up to the present time photometry of the continuous spectrum of the planets has hardly been attempted.

In this connection it is of interest to compare the data on the near infra-red spectrum of Uranus. Considering that the visual albedo of Uranus is somewhat higher than that of Saturn, and the heliocentric distances of the two planets are in the ration 2:1, one would expect the exposure ratio in the infra-red at about 5:1 to result in the spectrum of Uranus of about the same density as that of Saturn. This is definitely not so, as the ratio of exposure time is more nearly 50:1.

On the same IV–N plate (reproduced in Fig. 2) on which a strong spectrum of Saturn was obtained in 20 minutes, an exposure of 70 minutes failed to produce the slightest traces of the spectrum of Uranus. Only by widening the slit of the spectrograph by 30 percent, could I obtain a faint spectrum of Uranus in two hours on an I–N plate, which is considerably faster than a IV–N plate. The spectrum shows wide gaps corresponding to the groups of methane bands:

$\lambda6500-\lambda6700$
$\lambda6900-\lambda7400$
$\lambda7800-\lambda8100$
$\lambda8300-\lambda9000$.

The spectrum between the gaps, however, appears to be very similar to the spectrum of Jupiter or Saturn. There is no reason why the regions where no methane bands are present should be so faint unless there is a continuous absorption produced by some agent in the atmosphere of Uranus. This absorption must be much stronger in the near infra-red part of the spectrum of Uranus as compared with Jupiter and

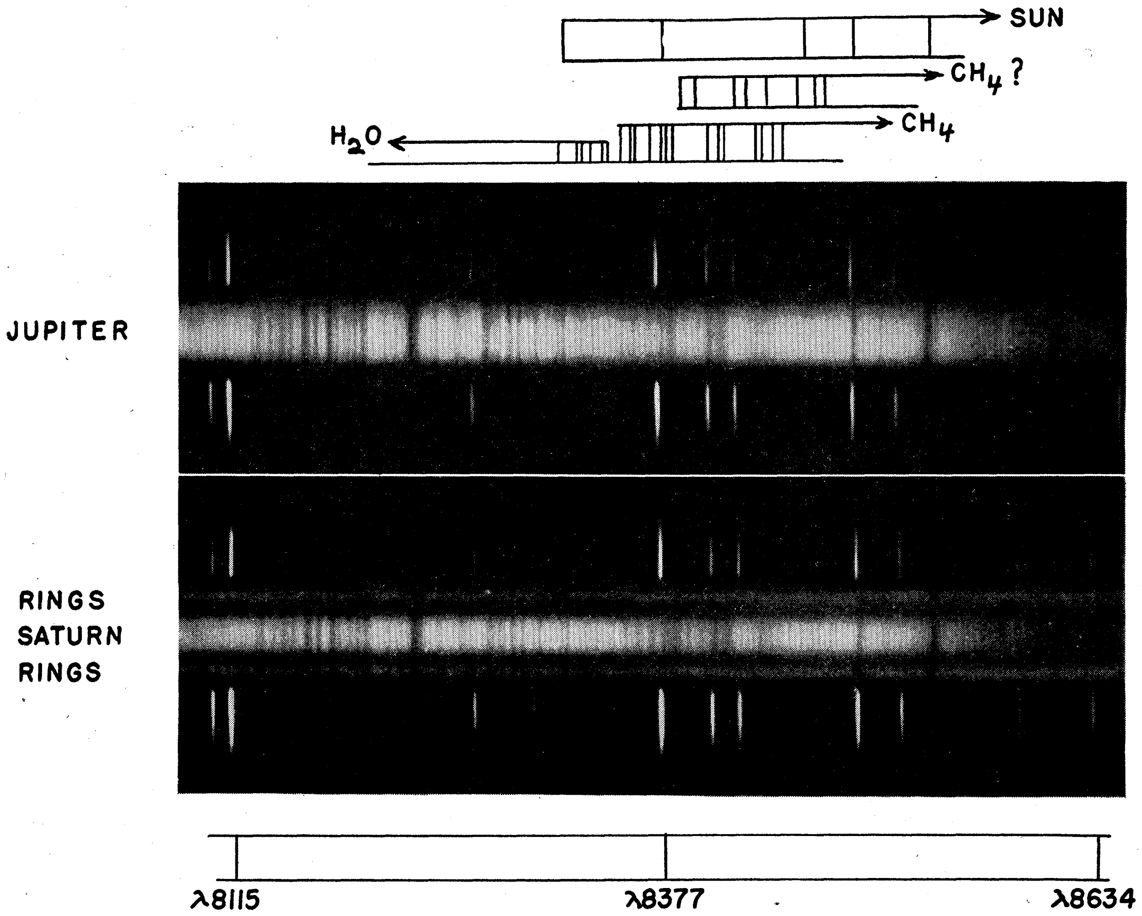

FIG. 2. Spectrum of Jupiter and Saturn on October 21, 1943 on emulsion IV-N (Eastman Kodak). Original scale 45 A/mm. Note that the water-vapor lines are somewhat stronger in the spectrum of Jupiter while the methane lines are stronger in Saturn. The solar lines are distinctly inclined, especially in Saturn owing to the rapid rotation of the planet. The solar and telluric lines are visible in the spectrum of the ring of Saturn, while methane lines are restricted to the body of the planet. Comparison spectrum neon and argon. CH_4 denotes lines observed in the laboratory; CH_4? denotes other lines probably due to methane.

Saturn. The common explanation of the green color of Uranus and Neptune when seen through the telescope is the presence of strong methane bands in their spectra cutting down the amount of orange and red light. This is certainly not true for Uranus as I showed some 15 years ago.[25] The maximum of intensity of the continuous spectrum of the planet is in the green, and the absorption bands play a minor role in the modification of the color.

The current status of the problems of planetary spectroscopy is illustrated by Fig. 2. It represents a portion of the spectra of Jupiter and Saturn taken on October 21, 1943 under identical instrumental conditions on Eastman spectroscopic plate IV–N. The only difference was the exposure time which for Jupiter was 10 minutes and for Saturn 20 minutes. We see the nearly symmetrical water-vapor band Z at λ8227 $(2\nu_1+\nu_2+\nu_3)$. The rotational Q-branch is in the center (the heaviest absorption), the R-branch is toward the longer wave-lengths, and the P-branch is toward the shorter wave-lengths. The Z band is somewhat stronger in Jupiter, as the altitude of Jupiter during the exposure was 50° and of Saturn 69°. There are five solar lines indicated on the reproduction of which the two strong lines to the longer wave-lengths belong to CaII. Both telluric lines and solar lines cut across the spectrum of Saturn's rings. While the telluric lines are perpendicular to the length of the spectrum the solar lines are sensibly inclined, especially in Saturn. This is due to the Doppler effect produced by the rapid rotation of the planets whereby the East limb was approaching the observer and the West limb was receding.

Between the water-vapor band and the first CaII line we notice a number of lines and since they are not visible in the spectrum of Saturn's rings, they must originate in the atmosphere of the planet, and are presumably due to methane. They are also somewhat stronger and more diffuse in the spectrum of Saturn although the telluric and solar lines are equally sharp in both spectra.

A reference to the literature on methane spectrum shows that 19 lines in a band centered at λ8400 were produced[35] in the laboratory with a path of 20.3 meters and a pressure of 10 atmospheres. If we compare the laboratory wave-lengths with those in the planetary spectra (correcting for the Doppler effect due to the relative velocity of the planets and the earth) we can identify 15 lines as belonging to methane but it is at once obvious that laboratory intensities are quite different from those observed in the planets. Some of the faintest lines in the laboratory are among the strongest in the planetary spectra and vice versa. Moreover, four of the lines measured by Vedder and Mecke are missing in the planetary spectra. Two of these are very close to the water-vapor and solar lines and may be concealed by them, but the other two are in spaces free from absorption lines, and are definitely absent.

However, in the spectra of the planets in the region investigated by Vedder and Mecke there are six other lines, probably methane, which were not photographed in the laboratory. These lines with three more lines form another vibrational transition centered at λ8430. It is probably the band designated $7\nu_4+\nu_3$ in Table IV. It is strange that this latter band, which as a whole is much fainter than the band measured by Vedder and Mecke, was reported in the spectra of the planets, while the band at λ8400 was never noticed. A careful measurement of the planetary spectra will no doubt result in a considerable extension of the known spectrum of methane.

The problem before us is to explain the behavior of methane bands in the planets. Obviously the discrepancy between the laboratory and astronomical spectra is due to the difference in physical conditions, presumably temperature and pressure. In order to interpret these differences and derive some information about the conditions existing in the atmospheres of the planets we need the data for hundreds of rotational transitions for the bands in question. At the present time, even vibrational transitions for many bands have not been determined with certainty.

Figure 3 represents the region of the more complex methane band at λ8610. Laboratory sources give no fewer than 95 rotational lines for this band, while the planetary spectra show at least 50 lines attributable to methane.

Figure 4 shows the region of the ammonia band at λ7930 in the spectrum of Jupiter. Its structure

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[35] H. Vedder and R. Mecke, Zeits. f. Physik **36**, 135 (1933).

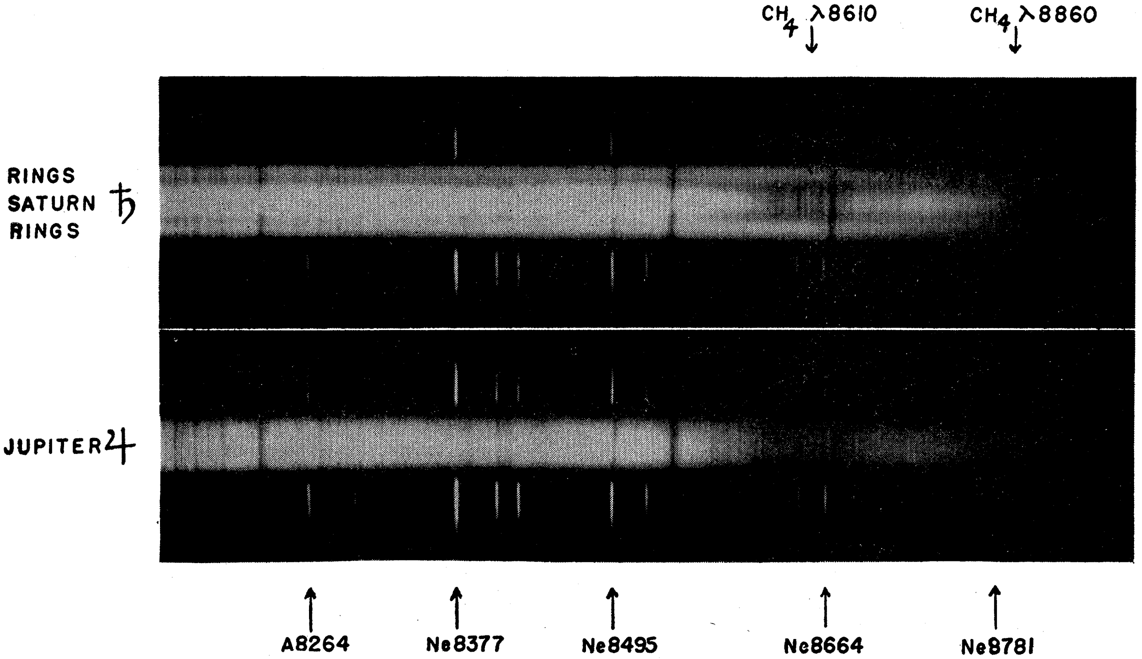

FIG. 3. Region of the strong methane bands in the spectra of Jupiter and Saturn. Portion of the same spectrograms as used in Fig. 2. Notice that the spectrum of Saturn is cut off near λ8800 by the strong methane band λ8860 but the spectrum of the rings can be followed farther into the infra-red.

is very different from methane bands and its rotational lines are exceedingly sharp. It is very weak in the spectrum of Saturn.

A few words can be said about the surface details so prominent on Jupiter. As has been mentioned before they are sometimes very stable formations, persisting several weeks, or even many years as in the case of the Great Red Spot. Other formations, however, are more like our clouds, forming and dissipating in a few days, if not hours.

My own observations[33] showed that the spectrum of the equatorial belts on Jupiter, so far as ammonia lines are concerned, differs little if at all from the spectrum of the free regions from the equator to the pole. V. M. Slipher[11] reports some difference. The green region of the continuous spectrum was found to be much weaker in the belts than on the equator, and the ammonia band at λ6460 in the belts was slightly weaker. Previous observations are even more emphatic in regard to the difference in the spectrum between the various parts of the disk. Millochau[36] in 1904 found that methane bands were reinforced in the spectrum of the south equatorial belt which was unusually strong that year. Belopolsky[37] in 1919 on the contrary found that all lines and bands were fainter in the belts than in the brighter portions of the planet. Vogel[38] speaks of the increase in intensity of planetary bands in the spectrum of Jupiter's belts as an established fact. Perhaps appreciable changes in the spectrum of the belts can be detected from time to time. These changes, if established, can be due to the variable height of clouds whereby the optical path of the reflected light of the sun must be changed.

Visually these formations are sometimes hardly noticeable, sometimes very striking in color, ranging from olive-green to dark red. There seems to be even a distinct periodicity in the change of color, with a period of about eleven years. There is also a rough symmetry in changes: when in one hemisphere the green color predominates, the other hemisphere is dark red.

No explanation of these phenomena is forth-

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[36] G. Millochau, Ann. Obs. D'Astronom. Meud. **2**, 273 (1906).

[37] A. Belopolsky, Bull. Acad. Imp. St. Petersburg [6] **3**, 874 (1919).

[38] H. C. Vogel, see reference 27, p. 33.

coming. Suggestions such as the Red Spot's being an island of frozen ammonia in an ocean of liquid hydrocarbons is hardly better than speculation. It must be a floating island since its longitude is slowly changing, but there has been no appreciable change in its latitude for the last seventy years. One remarkable spot observed in 1940–41 showed a clearly oscillatory motion superimposed in a general nearly uniform drift in longitude with a damping effect strongly indicated.[39] It now seems clear that these spots are atmospheric phenomena of some sort but Jovian meteorology may prove to be an exceedingly difficult subject.

It has been suggested[40] that the brilliant hues of Jupiter's clouds are produced by metallic sodium, but why should there be more sodium in one hemisphere than in the other, with a reversal of the picture a few years later? Similar belts exist in Saturn, but they do not show any coloration.

The decrease in the intensity of the ammonia bands in Saturn as compared with Jupiter is generally attributed to the difference in temperature. We have the same factor in the atmosphere of Jupiter alone if we consider the spectrum of the center of the disk and of the limb. At the center the sunlight penetrates deeper and the temperature should be higher. The spectrum of the east limb of Jupiter, just emerging from darkness, should show stronger bands of methane and fainter bands of ammonia. The spectrum of the east limb should thus resemble that of Saturn. Such an effect was reported by Menzel,[41] but a later and a more precise photometric study by Elvey and Fairley[42] showed that there is no appreciable difference between the spectrum of the center of the disk of Jupiter and its limbs, at least so far as the methane band λ6191A is concerned. As the rotational axis of Jupiter is almost perpendicular to the plane of its orbit we may expect considerably lower temperatures at the poles and the corresponding variation in the spectrum. Observations to settle this question were made by Eropkin,[43] and again no difference at all was observed in the intensity or contour of the methane band λ6191A. The ammonia band λ6430 was found to be somewhat stronger in the spectrum of the equatorial region as we should expect.

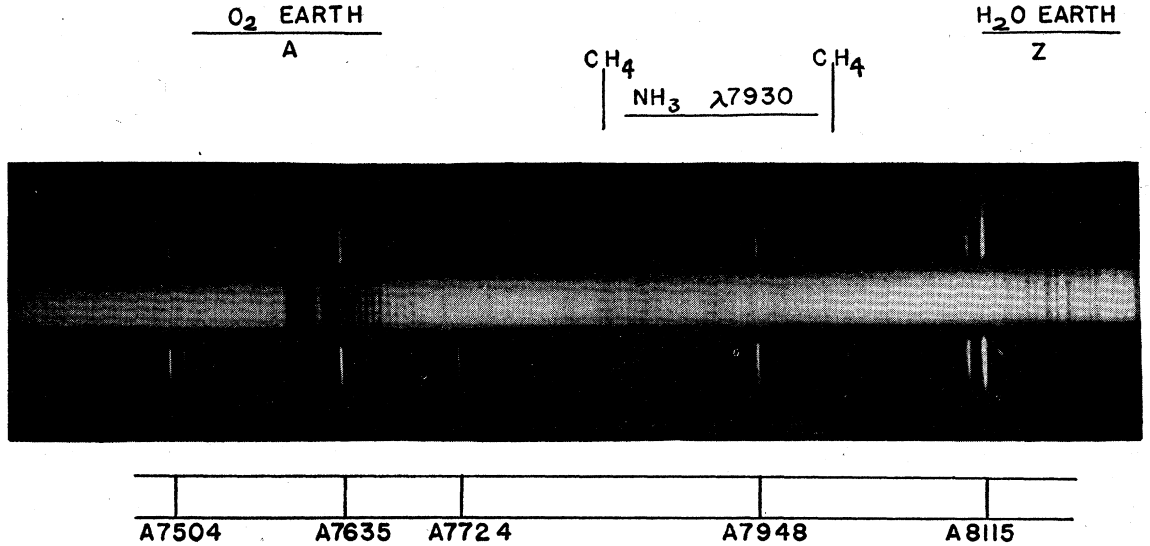

FIG. 4. Spectrum of Jupiter (October 21, 1943). Eastman Kodak emulsion IV-N. Ammonia band λ7930 consists of exceedingly fine lines quite different from the heavy absorption of methane. Comparison spectrum argon and neon.

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[39] B. M. Peek, Monthly Not. R.A.S. **101**, 70 (1941). The problem of the Red Spot is discussed by the same author in J. Brit. Astronom. Assoc. **50**, 2 (1939). An attempt to treat the recent spot as a solid floating in a fluid resulted in the value of the compressibility of the fluid 1.3×10^{-12} per atmosphere, which is some 10^7 less than the lowest figure observed in the laboratory.

[40] R. Wildt, Monthly Not. R.A.S. 99, 616 (1939).

[41] D. H. Menzel, Pop. Astronom. **35**, 489 (1927). It is quite obvious from the plates in this article that there is no appreciable difference in the intensity of methane or ammonia lines between the two limbs of the planet.

[42] C. T. Elvey and A. S. Fairley, Astrophys. J. **75**, 373 (1932).

[43] D. J. Eropkin, Comptes Rendus Ac. Sci. U.S.S.R. No. 4 (1933).

SATELLITES

The satellites of the planets are, with the exception of the moon, too faint for a detailed spectroscopic study. The moon as a whole faithfully reproduces the spectrum of the sun. It is known that some parts of its surface have high selective reflectivity. A spot near the crater Aristarchus is especially prominent on ultraviolet photographs. Spectra of different portions of the moon confirm this effect.[25]

Other satellites have been assumed to lack atmospheres on account of their small masses. The announcement[44] that Titan, the largest satellite of Saturn, shows in its spectrum methane bands was quite unexpected. The bands in Titan are somewhat weaker than in Saturn. It is shown on the basis of the kinetic theory of gases that not only Titan but Triton, the satellite of Neptune, could retain molecules of methane. The spectrum of Triton shows little evidence of methane, but the question cannot be considered closed. The spectra of the following satellites have been examined at the McDonald Observatory, but no methane bands were found:

Jupiter: Io, Europa, Ganymede, Callisto
Saturn: Rhea, Tethys, Dione.

GENERAL CONSIDERATIONS

The identification of methane and ammonia in the atmosphere of the major planets and of carbon dioxide in the atmosphere of Venus appears to have solved the planetary problem in its entirety. An attempt to interpret the occurrence of so few compounds in the planetary atmospheres has been made by Wildt.[45] His argument is based on the fact that all polyatomic molecules observed in the spectra of the planets are highly susceptible to the decomposition by the ultraviolet radiation of the sun. However, the data of photochemistry are incomplete and often contradictory and perhaps it is premature to build an involved hypothesis of the chemical processes in the planetary atmospheres.

According to Wildt the fundamental reaction in the atmospheres of the major planets is the decomposition of methane by ultraviolet radiation ($<\lambda 1300\text{A}$) and its subsequent formation:

$$CH_4 + h\nu \rightarrow H + CH_3,$$

$$CH_3 + H_2 \rightarrow CH_4 + H.$$

Therefore a large supply of free hydrogen is a necessary condition for this reaction. All other hydrocarbons are shown to be unstable under these conditions as their continuous absorption begins at a longer wave-length than that of methane.

This scheme leaves the existence of ammonia unexplained as its continuous absorption begins at considerably longer wave-lengths than in methane and some other hydrocarbons.

It is difficult to see what part the ultraviolet radiation of the sun could play in planetary atmospheres. Methane bands are produced in layers corresponding to hundreds of meters of optical path at standard conditions whereas 15 cm of methane are enough to produce a complete absorption in the wave-lengths longer than λ1820, a fact quoted by Wildt himself. The photochemical process, it would seem, can account only for a small fraction of methane producing absorption lines in the spectra of the planets. The situation is quite analogous to the action of the ozone layer in the stratosphere of the earth. The postulated abundance of hydrogen also seems questionable in view of the existence of Titan's atmosphere. Titan can retain methane but certainly not free hydrogen.[46]

In Venus the main reaction according to Wildt is:

$$\lambda < 1800\text{A}: CO_2 + h\nu \rightarrow O + CO$$

but the difficulty is in devising a process by which carbon monoxide can be oxidized into carbon dioxide. It should be recalled that there is no spectroscopic evidence of the presence of any appreciable quantity of free oxygen in the atmosphere of Venus.

Although the internal constitution of the planets is not the subject of this report, it is of interest to see how the new spectroscopic data

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[44] G. P. Kuiper, Astrophys. J. **100**, 378 (1944).

[45] R. Wildt, Astrophys. J. **86**, 321 (1937). The same author showed (Veroff Univ.-Sternwarte Göttingen, **38**, 1944) that the identification of some of the planetary absorption bands with the Chappuis bands of ozone (D. E. Eropkin, Comptes Rendus Ac. Sci. U.S.S.R. No. 5, 1933) is incorrect. Older identifications include water-vapor and even chlorophyll.

[46] Older reports of the progressive intensification of hydrogen lines in the spectra of the major planets have been shown both theoretically and observationally incorrect. Some lines are seemingly intensified by the superposition of methane bands.

have affected our ideas in this respect. Without any knowledge of the spectroscopy of the planets we can arrive at some conclusions based on the fact that all major planets have extensive atmospheres and their average density is very low. The pressures at the bottom of these atmospheres must be very high, and the planets themselves cannot be solid bodies of the same pattern as the earth. There must be comparatively small dense cores, surrounded by vast layers of light substance such as ice, on top of which are atmospheric gases highly condensed nearer the surface of ice. Such a model was suggested long ago by Jeffreys.[47] This idea was further developed by Wildt,[48] one of whose models for Jupiter is quoted here.

Jupiter has three layers with respective densities 5.50, 1.00, and 0.35 of water. The surfaces of discontinuity occur at 0.855 and 0.494 of the visible radius of the planet. The gaseous layer is then some 10,000 km deep and the pressure at the bottom of it is about 100,000 atmospheres. This gaseous layer can hardly be called an atmosphere as its lower portion consists of highly compressed liquid or even solidified gases, including hydrogen.

It is difficult to imagine anything else but such a model of the atmosphere of Jupiter, yet it is decidedly contradicted by the phenomena of clouds and belts, as well as by photometric measures of the planet. Schoenberg more than anybody else has contributed to the theory of light scattering and diffusion in planetary atmospheres. In his latest article[49] discussing the best available observational material, he comes to the conclusion that the only possible explanation of the processes in the atmosphere of Jupiter is the strong and continued volcanic activity.

It is evident that much is yet to be learned about the planets before a consistent theory of their atmospheres can be developed.

An application of the theory of polyatomic molecules to the study of the planetary spectra may contribute to the solution of some problems which up to the present time have not yielded much information:

(1) What is the actual temperature of the atmospheric layers to which the solar light penetrates in major planets? A study in the distribution of intensity in the rotational structure of methane and ammonia in different parts of the planetary disk may solve this problem,[50] and establish the temperature gradient in the planets.

(2) Why are the methane bands so strong in Uranus and Neptune? It is commonly accepted that in these planets the solar light penetrates to far greater depths as gaseous ammonia is removed by the low temperatures. However, in Saturn gaseous ammonia is practically absent yet the methane bands are only slightly stronger than in Jupiter. The striking increase in the intensity of the methane bands occurs between Saturn and Uranus with a drop in absolute temperature of only 27°.

(3) Why are only methane bands so prominent in the spectra of the major planets? Even if we accept photochemical arguments, the cycle of methane should result in a certain amount of other hydrocarbons. A thorough investigation of large dispersion spectrograms may settle this question.

(4) What is the nature of particles responsible for the scattering of light in the atmospheres of the planets? A detailed photometric investigation of the continuous spectrum of the planets is indicated.

(5) What is the nature of clouds visible on the surface of the planets? Either the change in the distribution of intensity in the continuous spectrum of the clouds or the modification of absorption lines in their spectra may contribute to the solution of this problem.

The atmospheres of the major planets present the problem of the behavior of matter under conditions of low temperature and high pressure, in striking contrast to the problem of stellar atmospheres. Further investigations of the spectra of the planets may shed light not only on the physical conditions prevailing in the planets, but may substantially contribute to the solution of the everlasting puzzle—the origin of the solar system.

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[47] H. Jeffreys, Monthly Not. R.A.S. **84**, 534 (1924). In this paper methane was suggested as a possible constituent of the atmospheres of the major planets as well as of the atmosphere of Titan, and of the Galilean satellites of Jupiter.

[48] R. Wildt, Proc. Am. Phil. Soc. **81**, 135 (1939).

[49] E. Schoenberg, *Festschrift für E. Strömgren* (Einar Munksgaard, Copenhagen, 1940), p. 181.

[50] This has already been done for Venus: A. Adel, Astrophys. J. **86**, 337 (1937).

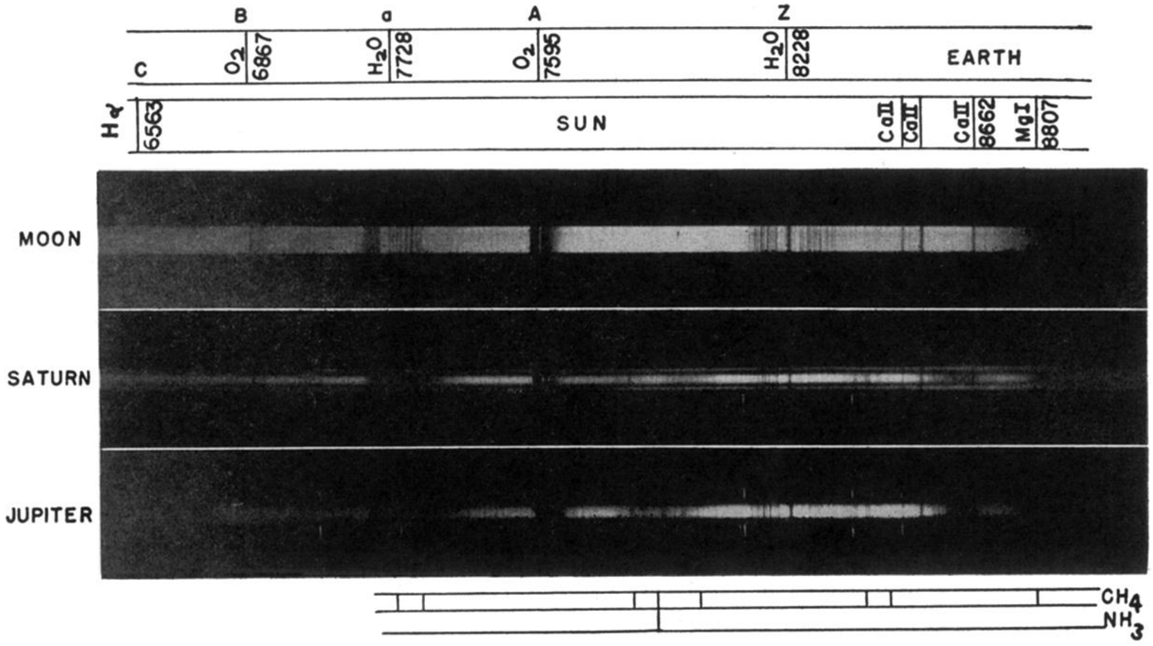

FIG. 1. Spectrum of the moon (upper) (November 1, 1944), of Saturn (center) (November 1, 1944) and of Jupiter (lower) (October 21, 1943). Eastman Kodak emulsion I-N for the moon and Saturn, and IV-N for Jupiter. Solar lines and telluric bands are common to all of these spectra. Some methane and ammonia bands are shown in the spectra of the planets. Note the sudden cut-off of the planetary spectra near λ8800 due to the strong methane absorption. Comparison spectrum neon and argon.

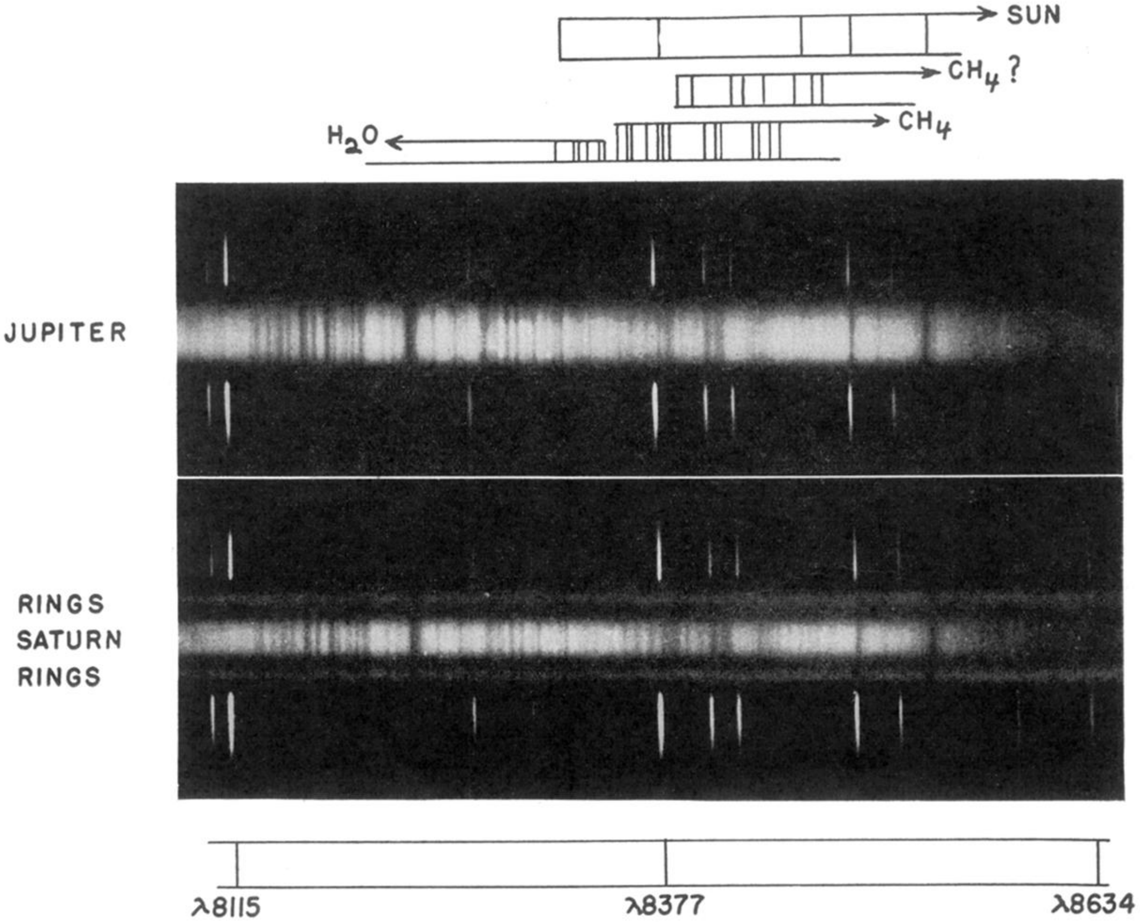

FIG. 2. Spectrum of Jupiter and Saturn on October 21, 1943 on emulsion IV-N (Eastman Kodak). Original scale 45 A/mm. Note that the water-vapor lines are somewhat stronger in the spectrum of Jupiter while the methane lines are stronger in Saturn. The solar lines are distinctly inclined, especially in Saturn owing to the rapid rotation of the planet. The solar and telluric lines are visible in the spectrum of the ring of Saturn, while methane lines are restricted to the body of the planet. Comparison spectrum neon and argon. CH_4 denotes lines observed in the laboratory; CH_4? denotes other lines probably due to methane.

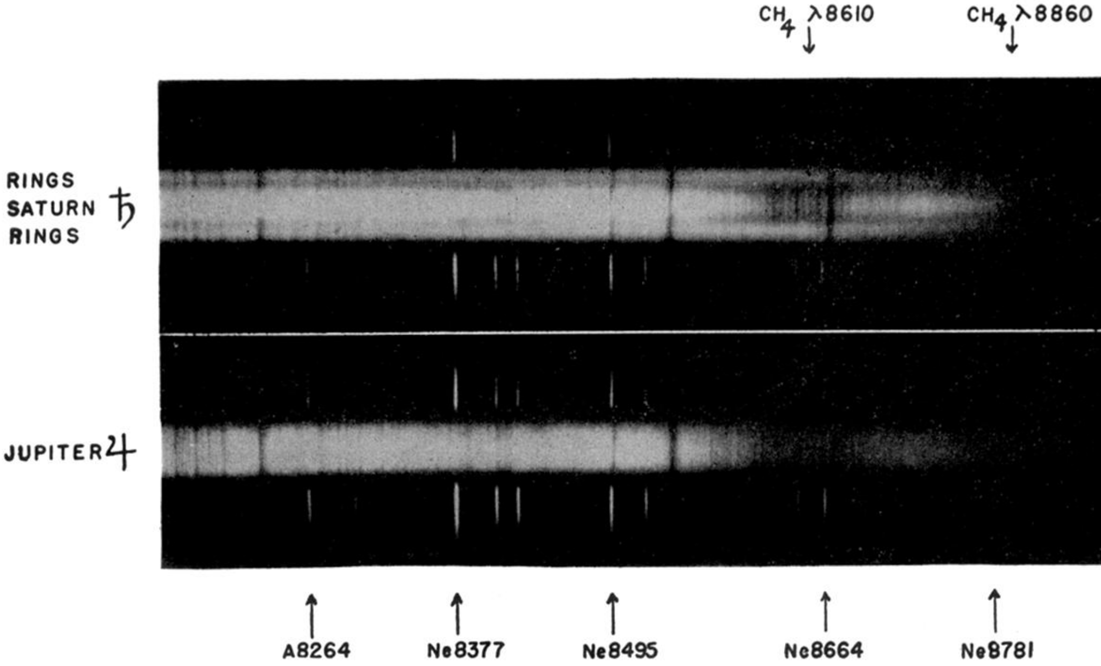

FIG. 3. Region of the strong methane bands in the spectra of Jupiter and Saturn. Portion of the same spectrograms as used in Fig. 2. Notice that the spectrum of Saturn is cut off near λ8800 by the strong methane band λ8860 but the spectrum of the rings can be followed farther into the infra-red.

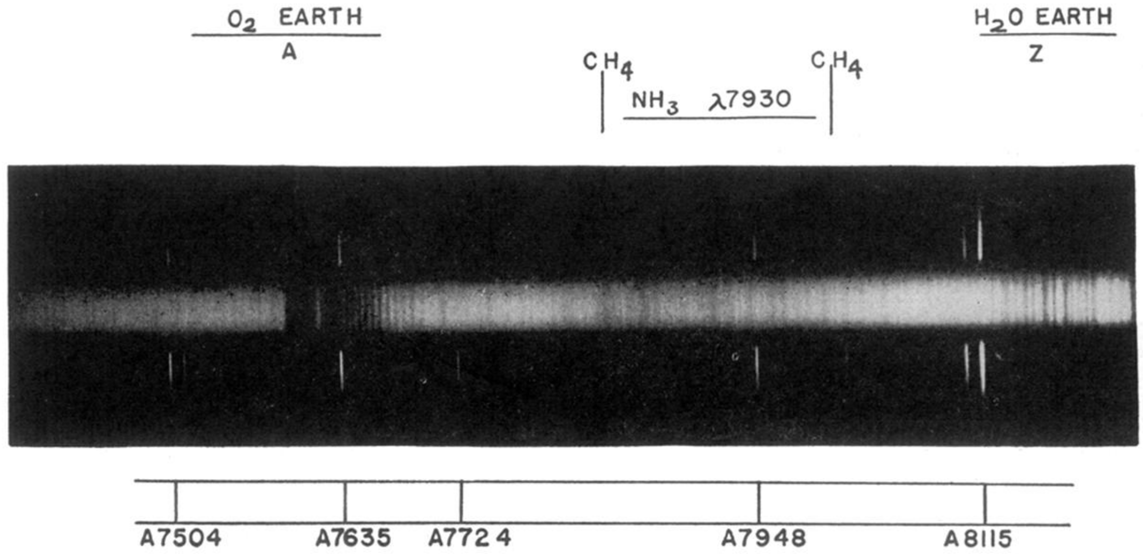

FIG. 4. Spectrum of Jupiter (October 21, 1943). Eastman Kodak emulsion IV-N. Ammonia band λ7930 consists of exceedingly fine lines quite different from the heavy absorption of methane. Comparison spectrum argon and neon.