TITAN: A SATELLITE WITH AN ATMOSPHERE*

GERARD P. KUIPER[1]
McDonald and Yerkes Observatories
Received August 21, 1944

ABSTRACT

Recently the ten largest satellites in the solar system, as well as Pluto, were observed spectroscopically. Only Titan was found to have an atmosphere of sufficient prominence to be detected, but Triton and Pluto require further study. The composition of Titan's atmosphere is similar to that of Saturn, although the optical thickness is somewhat less.

The presence of gases rich in hydrogen atoms on a small body like Titan is surprising and indicates that the atmosphere was formed after Titan had cooled off. Similar arguments, though less compelling, may be advanced for analogous conclusions in regard to the formation of the atmospheres of Mars, Venus, and the earth.

I. OBSERVATIONS

During a short stay at the McDonald Observatory during the winter of 1943–1944 the ten largest satellites of the solar system were observed with a one-prism spectrograph attached to the 82-inch reflector. Pluto had been observed twice on an earlier occasion. Panchromatic film was used, sensitive below 6600 A. The dispersion was 340 A/mm at $H\gamma$. With this combination the methane absorptions of the major planets are well shown (Pl. XV); but many lesser absorptions are, of course, lost. When Titan's spectrum was found to contain the methane absorption bands, a number of plates with higher dispersion were taken. Because of the limited time available, no exhaustive study of the subject could be made at this time.

The spectra presented here consist of several groups. Plate XV shows low-dispersion spectra on panchromatic film; Plate XVI, low-dispersion spectra on infrared film; Plate XVII, medium-dispersion spectra on panchromatic film; Plate XVIII, medium-dispersion spectra on infrared plates; and Plate XIX, medium-dispersion spectra in the photographic, as well as the infrared, regions. In all cases planetary spectra, taken under similar conditions, have been added for comparison.

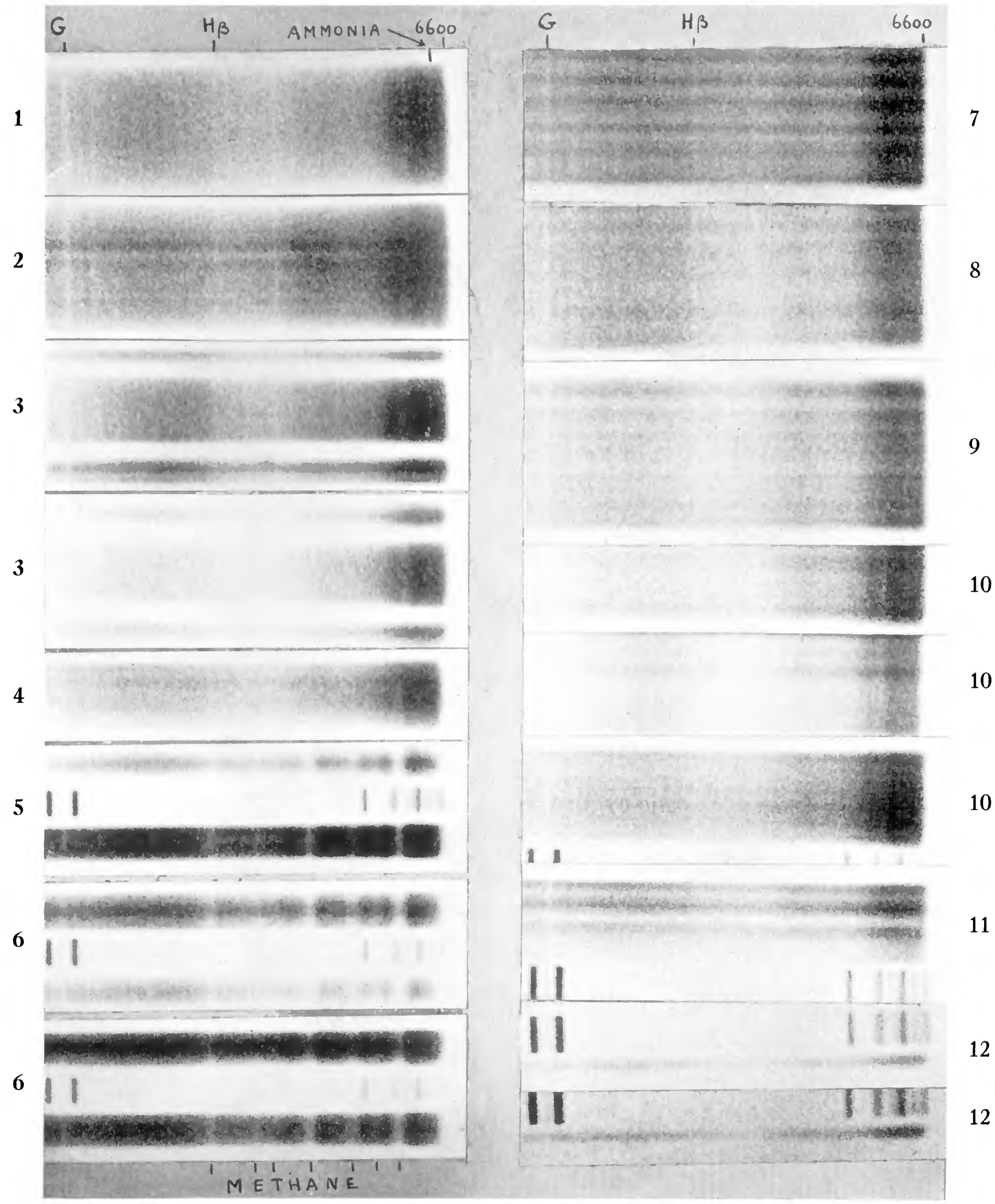
In addition to the major planets and the moon, the following objects were observed with low dispersion in the panchromatic region: Jupiter I, II, III, and IV; Saturn's satellites Titan, Rhea, Tethys, and Dione; Neptune's satellite Triton; and Pluto. Some of the spectra are shown in Plate XV. The methane absorption at 6190 A is striking in the three spectra of Titan shown, in marked contrast to that of Rhea and with the satellites of Jupiter. The results on Tethys and Dione were also definitely negative, but Triton may show a trace of the 6190 A band of methane. This object will be further investigated, as well as Pluto, for which two spectra were obtained with the dispersion of 720 A/mm at $H\gamma$. It is certain, however, that if Triton and Pluto have a methane atmosphere the absorptions are very much weaker than for Neptune and probably weaker than for Jupiter and Titan.

Plate XVI shows the objects for which infrared spectra of low dispersion were obtained. The most striking feature is the 7260 A band of methane. It is clearly present on Titan but is not present on the satellites of Jupiter or on the ring of Saturn. Because of field curvature the spectrograph used here required film, and the available 1N film appeared to be about two hundred times slower than panchromatic film. This condition restricted the infrared series of Plate XVI to the brighter objects.

* *Contributions from the McDonald Observatory, University of Texas,* No. 99.

[1] This paper was completed while the author was on leave of absence for war research at the Radiation Laboratory, O.S.R.D., Cambridge, Massachusetts.

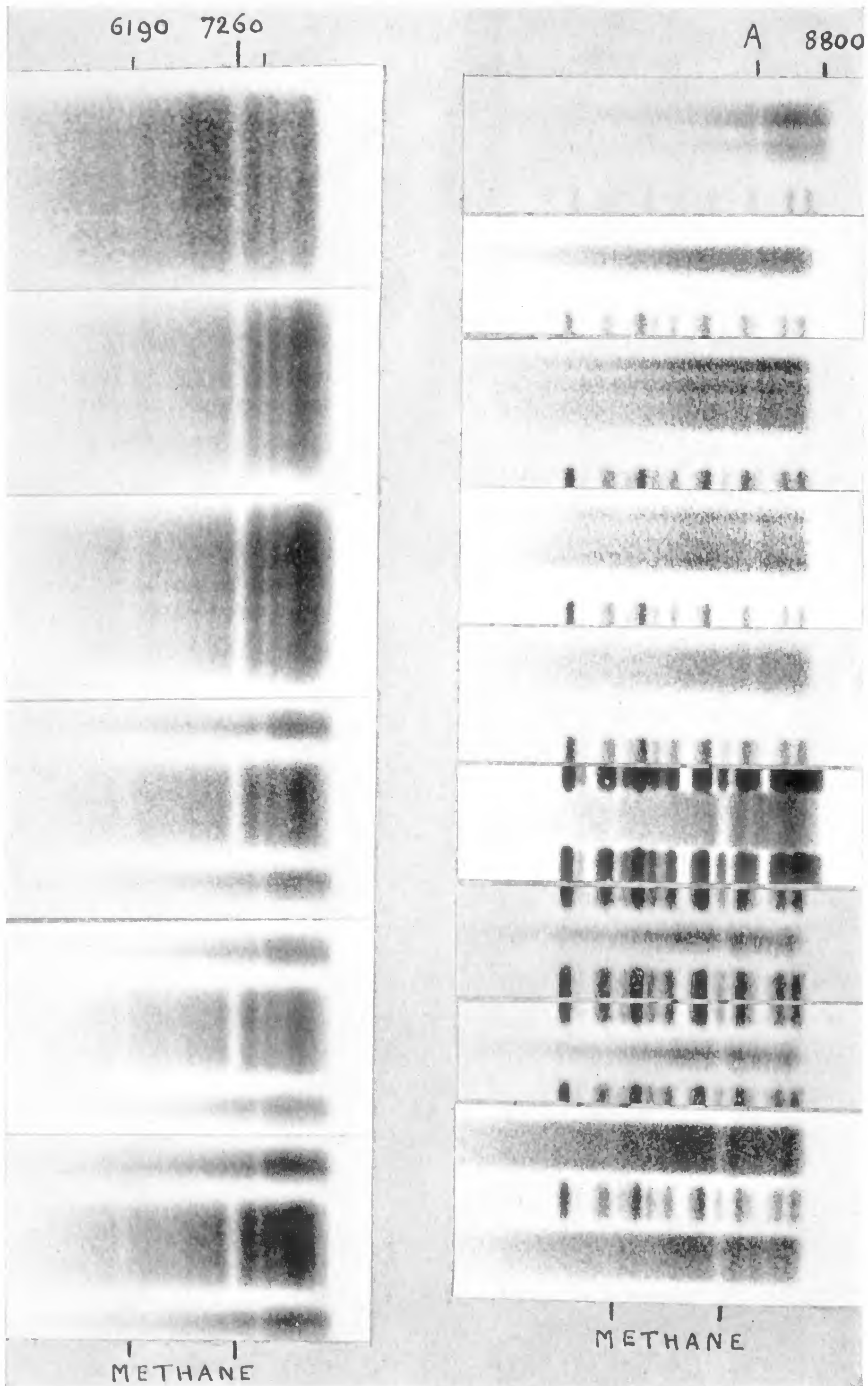
PLATE XV



LOW-DISPERSION SPECTRA ON PANCHROMATIC FILM

1. Jupiter, equator
2. Jupiter, through poles (belts show)
3. Saturn and ring
4. Saturn, through poles
5. Uranus
6. Neptune
7. Jupiter II
8. Jupiter III
9. Jupiter IV
10. Titan
11. Rhea
12. Triton

PLATE XVI



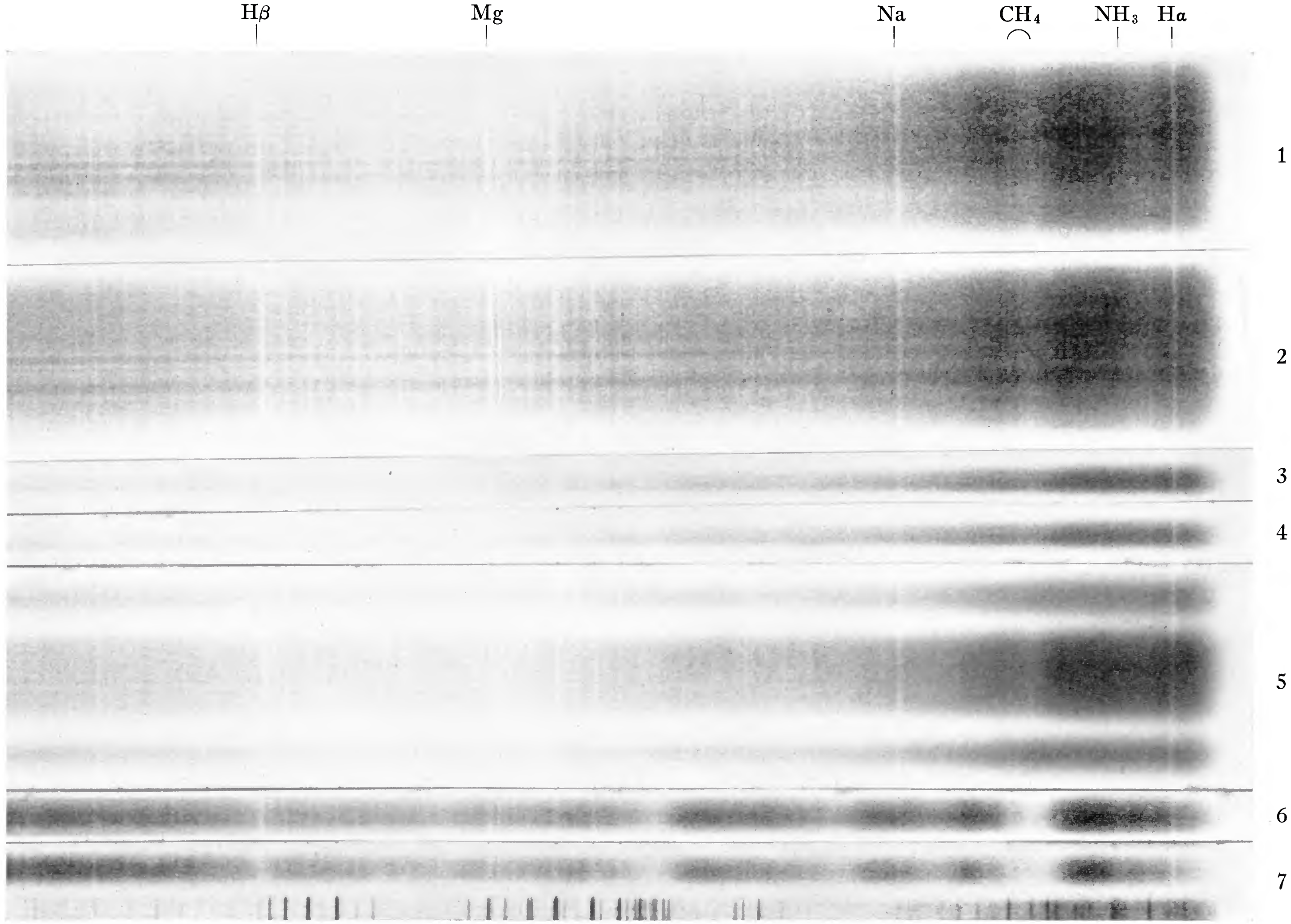
LOW-DISPERSION SPECTRA ON INFRARED FILM

1, 2. Jupiter
3. Saturn and ring
4, 5. Jupiter I
6. Jupiter II
7. Jupiter III
8. Jupiter IV
9. Saturn
10. Titan
11. Jupiter

The sensitivity-curve of the emulsion used in exposures 2, 3, 4, and 9 is somewhat different from the others.

1944ApJ...100..378K

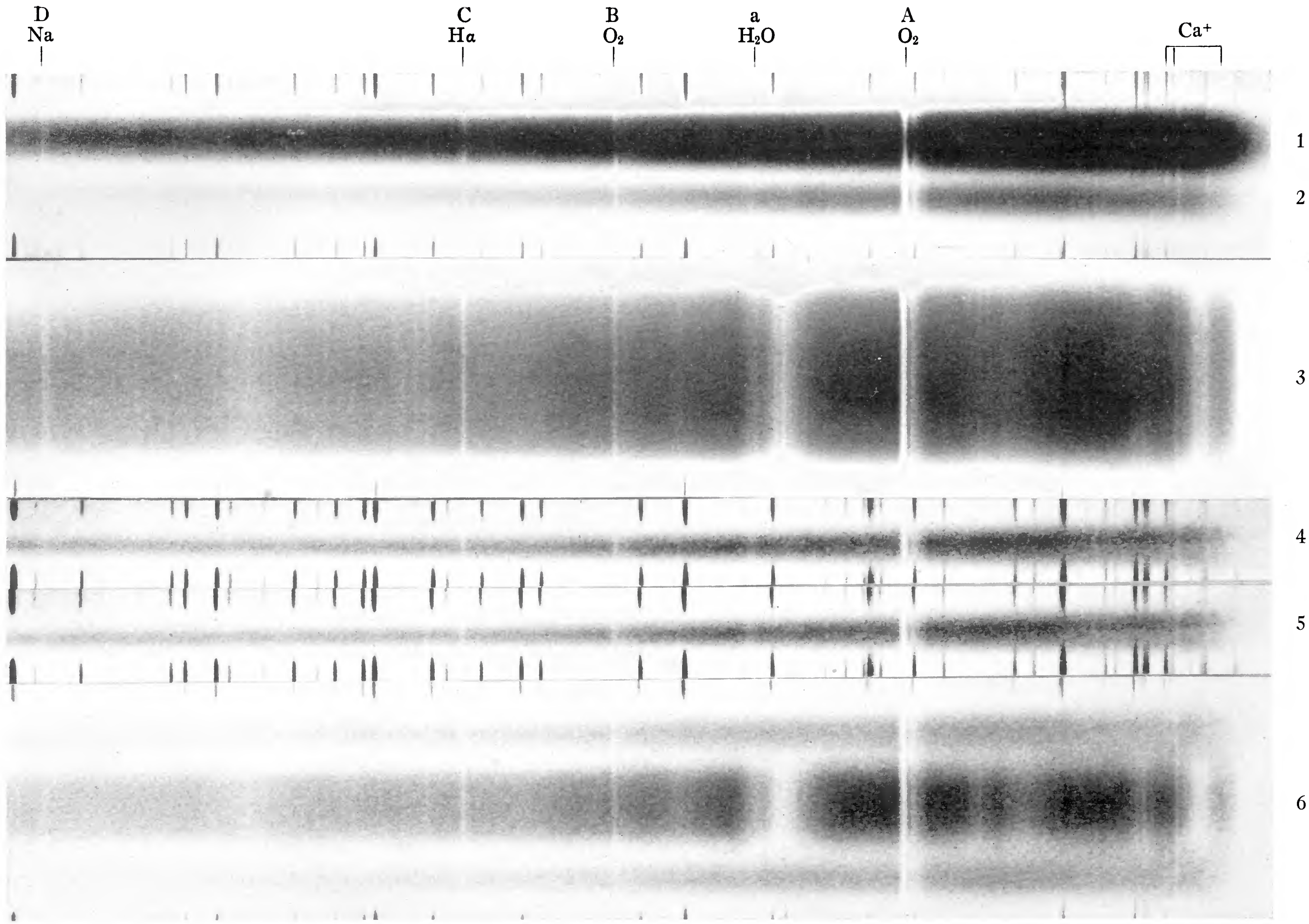
PLATE XVII



MEDIUM-DISPERSION SPECTRA ON PANCHROMATIC FILM

1, 2. Jupiter 3, 4. Titan 5. Saturn and ring 6. Uranus 7. Neptune

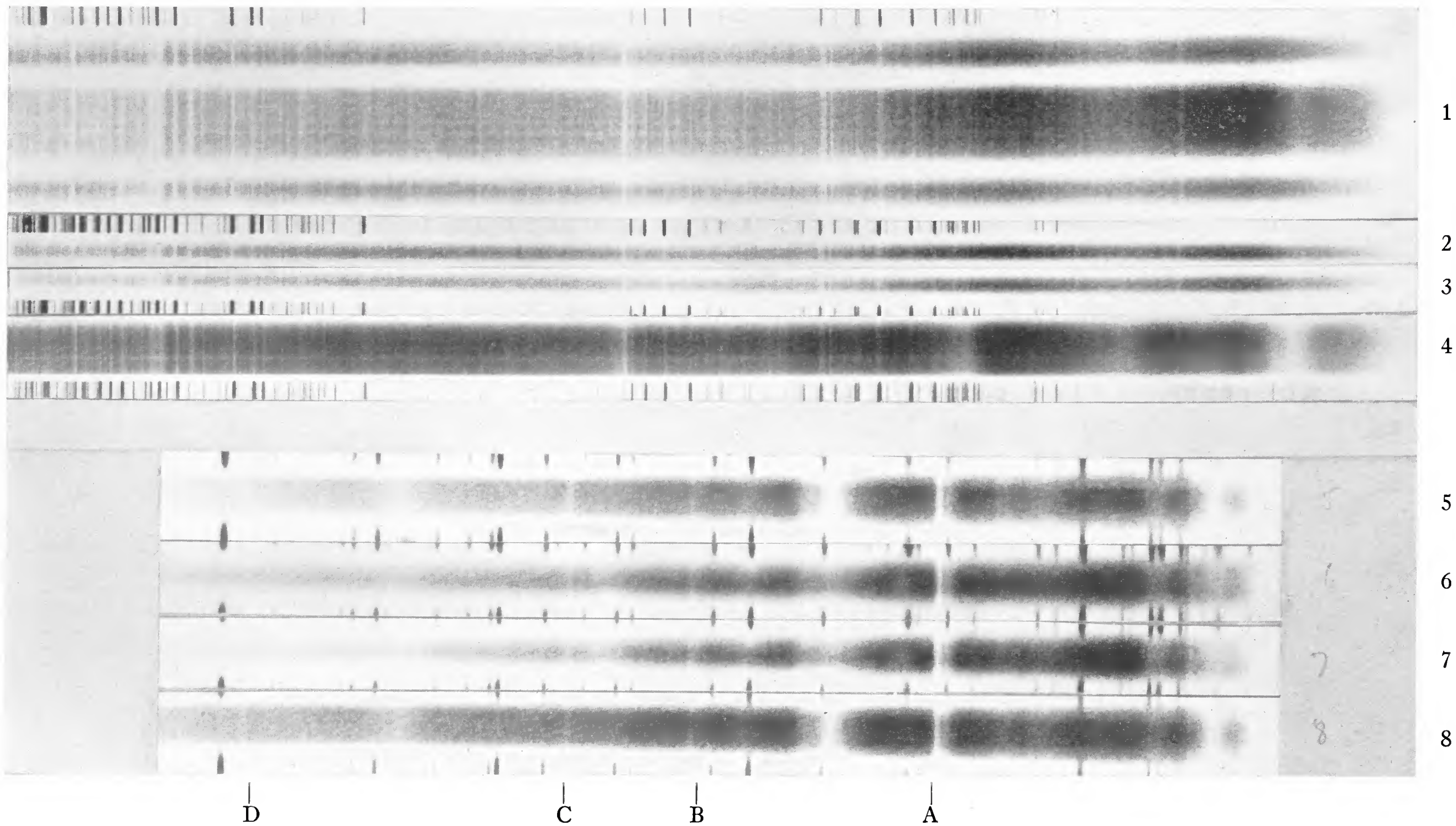
PLATE XVIII



Medium-Dispersion Spectra, Infrared Plates

1, 2. Mars 3. Jupiter 4, 5. Jupiter III 6. Saturn and ring

PLATE XIX



MEDIUM-DISPERSION SPECTRA

1–4. Saturn, Titan, and Uranus, visual region 5, 8. Saturn, infrared 6, 7. Titan, infrared

Plate XVII shows in the center two spectra of Titan (reproduced from the same negative), with spectra of the major planets added for comparison. The large Cassegrain spectrograph was used, with two quartz prisms and a curved plateholder. The dispersion is about 60 A/mm at $H\gamma$. The width of the methane band is so great that the larger dispersion in Plate XVII, as compared to Plate XV, does not lead to a corresponding increase of visibility. The rings of Saturn show the true solar spectrum.

With the aid of a photometer constructed by Dr. E. Dershem some density measures were made from 6000 to 6600 A on spectra of both Saturn and Titan. The density-curves are very similar but show that the methane band λ 6190 A is slightly shallower on Titan. The presence of the ammonia band at λ 6400 A is suspected, but additional plates are needed for a final answer.

The spectra of Plate XVIII were obtained on Eastman 1N plates and with glass prisms. The dispersion is about 26 A/mm at $H\gamma$ and about 140 A/mm at 7000 A. The spectrograph had not been used in the infrared before and was not designed for this region. The definition is remarkably good, although some astigmatism is apparent from the vertical dimensions in the spectra. The comparison spectrum is neon. The 1N plates were ten times faster than the film used in Plate XVI; an additional factor of 6 was gained by hypersensitization in an ammonia bath. In this manner the exposure times required in the infrared for an orange-colored light-source (Mars, Titan) were only about three-fourths of the times required in the red with the same spectrograph.

The objects shown in Plate XVIII are Mars (two exposures), Jupiter, Jupiter III (two prints of the same negative), and Saturn with its ring; the region covered is from 5800 to 8800 A. The plates were not hypersensitized. It is seen that Jupiter III does not show any trace of the methane or the ammonia bands. Its spectrum was obtained in 100 minutes, with the slit width somewhat increased.

Finally, Plate XIX shows two sets of spectra. The upper half is similar to Plate XVII but shows Titan in the photographic region compared to Saturn and Uranus. The only visible deviation from the solar spectrum is the λ 6190 A band of methane, as is seen from a comparison with Saturn's rings.

The lower half of Plate XIX shows Titan in the infrared (two central spectra, derived from one negative), compared to Saturn (two outer spectra). Quartz prisms were used, which gave a slightly lower dispersion in the infrared and a corresponding gain in speed (dispersion 60 A/mm at $H\gamma$ and about 200 A/mm at 7000 A). The plates of Saturn were not ammoniated; the exposure times were 5 and 15 minutes. These plates were kindly taken by Dr. Struve after the writer had left. The Titan plate was ammoniated; the exposure time was 4 hours. The same wide slit was used for both Titan and Saturn.

On the whole, there appears to be a close resemblance between the spectrum of Titan and that of Saturn; but the methane bands on Titan are definitely weaker. There appear to be some anomalous intensity ratios, as, for example, in the double band near λ 7200 A; but further plates are needed for a closer study.

The color contrast between Titan and Saturn shown by the spectra is striking. This is in agreement with telescopic observation, which shows Titan to be orange, like Mars. Saturn, in turn, is more yellow than its ring, as is shown by Plates XVIII (bottom) and XIX (top), a fact previously noted by V. M. Slipher.[2]

Thus, with the reservation stated regarding Triton, it appears that Titan is the only satellite in the solar system having an atmosphere detectable with the means here employed. It is of special interest that this atmosphere contains gases that are rich in hydrogen atoms; such gases had previously been associated with bodies having a large surface gravity. We shall return to this point later. The total thickness of the atmosphere is comparable to, but somewhat less than, that of the observable layers of Saturn and Jupiter, for which Slipher and Adel estimate 0.5 mile-atmospheres of methane gas.[3]

[2] "George Darwin Lecture," *M.N.*, **93**, 657, 1933.

[3] Th. Dunham, Jr., *Pub. A.S.P.*, **51**, 272, 1939.

It is somewhat surprising to find the statement by J. H. Jeans:[4] "An atmosphere has been observed on Titan," and his reference to "the suspected atmospheres on two of Jupiter's satellites." The writer has been unable to find an astronomical source for these statements. Apparently, they are not based on spectroscopic observations and have not been generally accepted, since other writers [5,6,7] make no mention of them. It is difficult to see how ordinary visual observations could have ascertained the presence of an atmosphere on bodies less than 1″ in diameter; in fact, such a thing would seem impossible.

II. MASSES OF THE OBSERVED OBJECTS

Dr. Dirk Brouwer has been kind enough to select from the various published mass determinations the ones that are, in his judgment, the most reliable. He made this compilation in February, 1944. With Dr. Brouwer's permission his list is reproduced in Table 1 of this paper.

Dr. Brouwer made the following additional comments:

The mass of Rhea is practically unknown. There is an estimate by H. Struve of the ratio Rhea/Saturn = 1/250,000, but I would not give this any weight. Woltjer's mass of Titan is still the best. The masses of Tethys and Dione are quoted from G. Struve. H. Struve for Tethys and Woltjer for Dione had arrived at essentially the same masses. . . . . There is no dynamical determination of the masses of the Uranus satellites. . . . . Alden's mass of Triton is to be used; he had the use of a very accurate ephemeris.

The mass of Pluto is very well determined by its perturbation on Neptune. The same mass satisfies the modern latitude observations [of Neptune] and gives a reasonable residual in longitude for the pre-discovery observations by Lalande in 1795. In practically all my work I have used 0.25×10^{-5}, but any mass between 0.25 and 0.35×10^{-5} will satisfy the observational material nearly equally well. The Lalande residual is improved by the larger mass, but oneshould not stress this too much. There remains for 1795 a residual in latitude of about $-1\overset{''}{.}5$, that cannot be removed by any reasonable adjustment of the orbital elements of Neptune or the mass of Pluto, and a mass of 0.25×10^{-5} would leave only a slightly larger residual in longitude.

III. DISCUSSION

Table 2 shows, for the planets and the satellites, the quantities which determine the stability of the atmospheres. The masses, radii, and densities are expressed in terms of the earth; the data were taken from Table 1 and from Russell, Dugan, and Stewart's *Astronomy*. Radii followed by a colon were derived from magnitudes and assumed albedos.

The computed densities are in some cases improbably low. It may be assumed that the adopted albedos and possibly the magnitudes are responsible for these abnormal results. Since we are dealing with a group of presumably similar small bodies, the assumption of a constant density may be less dangerous than the assumption of constant albedo; moreover, for equal errors in the assumed values the radii are more accurately determined from the densities than from the albedos. Also, the use of the (uncertain) magnitude is avoided.

Table 2 gives two lines for satellites whose computed densities differ considerably from 0.5 times the earth (2.76 times water), the average value adopted for small satellites. Except perhaps for Jupiter III and IV, for which the diameters were measured, the lower entries are probably closer to the truth.

The case of Pluto is puzzling. Either the mass is much smaller, and in reality resembles that of Triton, or the albedo is low and the planet presents a disk of about $0\overset{''}{.}5$. This point must be cleared up before the stability of an atmosphere can be discussed.

[4] *Dynamical Theory of Gases* (4th ed.), p. 348, Cambridge, 1925.

[5] Russell, Dugan, and Stewart, *Astronomy*, 1926–27.

[6] H. N. Russell, *The Solar System and Its Origin*, 1935.

[7] Th. Dunham, Jr., "Knowledge of the Planets in 1938," *Pub. A.S.P.*, **51**, 253, 1939.

The velocity of escape is given by

$$V_{\text{esc}} = \sqrt{\frac{2GM}{R}} = \sqrt{\frac{M}{R}} \times 11.3 \text{ km/sec} , \tag{1}$$

in which both M and R are expressed in terms of the earth. This quantity is listed numerically in Table 2, fifth column.

An atmosphere becomes unstable during astronomical intervals if the root-mean-square velocity of the molecules, V_m, becomes an appreciable fraction of V_{esc} (say, more than one-fifth, a value examined by Jeans).

$$V_m \propto \sqrt{\frac{T}{\mu}} , \tag{2}$$

if T is the Kelvin temperature and μ the molecular weight of the gas.

TABLE 1

Object	Mass of Satellite / Mass of Primary	Mass / Mass of Sun $\times 10^7$	Authority
J I.	0.0000381 ± 30 (p.e.)	0.364	De Sitter*
J II.	248 ± 5	0.237	De Sitter*
J III.	817 ± 10	0.780	De Sitter*
J IV.	509 ± 40	0.486	De Sitter*
Tethys.	$1 \div 876,400$	0.00326	G. Struve†
Dione.	$1 \div 541,300$	0.00529	G. Struve†
Titan.	$1 \div 4033$	0.709	Woltjer‡
Triton.	0.00128 ± 23 (p.e.)	0.66	Alden§
Pluto.	. . . .	28 ± 8 (p.e.)	Nicholson and Mayall‖
Pluto.	. . . .	25 ± 3	Brouwer,¶, ††
Pluto.	. . . .	30 ± 3	Wylie**, ††

* W. de Sitter, "George Darwin Lecture, 1931," *M.N.*, **91**, 706, 1931.

† G. Struve, *Pub. Berlin-Babelsberg*, **6**, Part IV, 56, 1930.

‡ J. Woltjer, Jr., *Ann. Leiden*, **16**, Part III, 66, 1928.

§ H. L. Alden, *A.J.*, **50**, 110, 1943.

‖ S. B. Nicholson and N. U. Mayall, *Ap. J.*, **73**, 1, 1931; *Mt. W. Contr.*, No. 417. Based upon longitudes only; i.e., depends principally upon Lalande's 1795 observations.

¶ D. Brouwer, *Pub. A.A.S.*, **10**, 8, 1940.

** L. R. Wylie, *A.J.*, **49**, 101, 1941.

†† Based upon both longitudes and latitudes; essentially the same material. Wylie used Newcomb's tables; Brouwer, a numerical integration. The latter differs extremely little from the tables. From a discussion of various solutions with different weighting I would consider 28 ± 3 the best result.

The value of T varies greatly through the solar system, roughly as $r^{-1/2}$, if r is the distance to the sun. Therefore, by using the parameter, $V_{\text{esc}} \cdot r^{1/4}$ (cf. Table 2, col. 7), we have eliminated the temperature effect on the stability. Since the variation in $\sqrt{\mu}$ is probably not large ($CH_4 = 16$; $NH_3 = 17$; $N_2 = 28$; $O_2 = 32$; $CO_2 = 44$) the figures in the last column of Table 2 are a suitable basis for comparison.

The order of decreasing atmosphere stability appears to be: Jupiter, Saturn, Neptune, Uranus, earth, Venus, Triton, Mars, Titan, J III, J IV, J I, J II, Mercury, moon, etc.

Excepting Triton, for which no atmosphere has yet been established, we find that atmospheres drop out between Titan and Jupiter III. Both boundary-line cases have been well observed.

Jeans has shown that an atmosphere is stable for astronomical periods if $V_m < 0.2\ V_{esc}$. For Titan the right-hand member of this inequality is 1.06 km/sec when reduced to $r=1$. The value of V_m will depend on the albedo and the rate of rotation. Assuming the limiting cases of no rotation and vanishing albedo, the temperature at $r=1$ equals 392° K.[8] The corresponding upper limit of V_m is 0.78 km/sec for CH_4, 0.76 km/sec for NH_3, and 0.47 km/sec for CO_2; but for H_2 it is 2.20 km/sec. Evidently the gases revealed by the spectroscope are stable components of the atmosphere, but hydrogen would escape in a matter of days.

TABLE 2

Body	Mass ⊕	Radius ⊕	Mean Density ⊕	V_{esc} (Km/Sec)	r	$V_{esc} \cdot r^{1/4}$ (Km/Sec)
Earth	1.00	1.00	1.00	11.3	1.00	11.3
Moon	0.0122	0.273	0.60	2.4	1.00	2.4
J I	0.0121	0.293	0.48	2.3	5.20	3.5
J II	0.0079	0.247	0.52	2.0	5.20	3.1
J III	0.0259	0.404	0.39	2.9	5.20	4.3
		0.373	0.50	3.0		4.5
J IV	0.0161	0.406	0.24	2.2	5.20	3.4
		0.318	0.50	2.5		3.8
Titan	0.0235	0.33	0.65	3.0	9.54	5.3
Rhea	0.00038:	0.137:	0.15:	0.60	9.54	1.1
		0.091	0.50	0.73		1.3
Dione	0.00018	0.094:	0.21:	0.49	9.54	0.9
		0.071	0.50	0.56		1.0
Tethys	0.00011	0.102:	0.10:	0.37	9.54	0.6
		0.060	0.50	0.48		0.8
Triton	0.022	0.39:	0.37:	2.7	30.1	6.3
		0.35	0.50	2.8		6.6
Pluto	0.93:	0.4:	....	....	....	....
Venus	0.81	0.973	0.88	10.3	0.723	9.5
Mars	0.108	0.531	0.72	5.1	1.524	5.7
Mercury	0.04	0.39	0.67	3.6	0.387	2.9
Jupiter	316.9	10.95	0.24	61.	5.20	92.
Saturn	94.9	9.02	0.13	36.6	9.54	64.
Uranus	14.7	4.00	0.23	21.7	19.2	45.
Neptune	17.2	3.92	0.29	23.7	30.1	55.

The stability of Titan's atmosphere would be endangered by a substantial increase in its temperature. Doubling it, i.e., raising it from 100°–125° K to 200°–250° K, would already jeopardize the permanence of CH_4; a still greater increase would cause a very rapid dissipation. Consequently, if Titan has gone through a period with a high surface temperature, as is commonly assumed to be true for all bodies in the solar system, then *it follows that Titan's atmosphere was formed subsequent to that period.* With almost equal force this conclusion follows for Mars, and to a lesser extent for Venus and the earth. In each of these cases all or nearly all of the atmosphere must have escaped from the crust after the crust was essentially cooled off.

The composition of Titan's atmosphere is in striking contrast to that of the earth

[8] Russell, Dugan, and Stewart, *op. cit.*, p. 541.

(N_2, O_2, H_2O, etc.) and of Venus (CO_2). Also, as we have seen, under terrestrial temperatures Titan's atmosphere would rapidly dissipate. On the other hand, the same factors indicate a genetic relationship to Saturn (or the other major planets). They make it highly probable that Titan was formed within the Saturn system and show definitely that Titan was not a product of capture from an (elliptical) orbit extending to the interior regions ($r \ll 5$) of the solar system.

As has been remarked above, the color of Titan is orange, in marked contrast with Saturn and its other satellites or with Jupiter and its satellites. It seems likely that the color is due to the action of the atmosphere on the surface itself, analogous to the oxidation supposed to be responsible for the orange color of Mars.[6]

It has recently been suggested that the atmosphere on Titan was predicted theoretically. Actually, as we have remarked, an observation of doubtful status preceded the theoretical discussion and was used to substantiate it. The nature of the problem is such that a complete theory of the origin of the solar system would be required before it could be predicted which bodies would have atmospheres and what their composition would be. Such a theory does not exist. The kinetic theory of gases can be used only to *deny* the existence of an atmosphere of specified composition on bodies which are too small or too hot at present. An affirmative statement would have to be based on the history of the case. In fact, something is learned about this history from the somewhat unexpected result that Titan has an atmosphere.