

NO. 29. COMPARISONS OF LABORATORY AND PLANETARY SPECTRA, I: THE SPECTRUM OF JUPITER FROM 9000-10,100A

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ABSTRACT

Absorption spectra of several gases are compared with spectra of Jupiter over the wavelength interval 9000-10,100A. The absorption features in the Jovian spectra are identified and include a new band system of ammonia. Upper limits on the abundances of CH_3NH_2 , C_2H_4 , C_2H_6 , SiH_4 , CH_3D , and HD are determined, and a limiting value for the ratio D/H in the Jovian atmosphere is derived.

1. Introduction

The region of the Jovian spectrum which is the subject of this investigation is of particular interest for two reasons. First, it has not been thoroughly studied in the past and contains a number of absorption features which have not been positively identified. Second, there is the possibility of detecting gases which may be *expected* to be present in the Jovian atmosphere in addition to the well-known constituents since some of these gases have relatively strong absorptions in this wavelength interval. Bardwell and Herzberg (1953), in discussing the possibility of detecting SiH_4 and CH_3D in the atmospheres of the outer planets, gave a brief list of absorption bands occurring in this region of the Jovian spectrum which they had compiled from the work of several observers. They noted that Vedder and Mecke (1933) had reported a strong absorption due to methane at 9706A from a laboratory investigation of this gas and concluded that methane was responsible for the band at 9700A which had been observed in the spectrum of Jupiter. The identification of the other absorption features was secondary to these authors' purpose and consequently was not pursued. In the present paper, recently obtained laboratory spectra of several gases are compared with spectra of Jupiter taken by Dr. G. P. Kuiper at the McDonald Observatory in 1954 and 1955. These spectra are of a higher quality than those published previously, and permit a detailed identification of the various absorptions occurring in this region, as well

as provide a means for setting upper limits on the abundances of certain gases considered to be probable constituents of the Jovian atmosphere.

2. Equipment and Experimental Procedure

Absorption spectra of the gases investigated were obtained with the help of a two-meter multiple path absorption tube on loan from the National Research Council of Canada through the courtesy of Dr. G. Herzberg. The design of this type of apparatus has been described elsewhere (Herzberg, 1952); its great advantage lies in the possibility of obtaining long optical paths in a relatively small space. With this particular tube a total path length of 80 meters is attainable. It is also possible to vary the pressure and temperature of the gas in the tube so that a wide variety of physical conditions can be reproduced. In the present investigation the tube was allowed to remain at room temperature at all times, and except for methane (which required a pressure of 5 atm to match the Jovian amount) all gases were studied at atmospheric pressure. A simple tungsten-filament lamp served as a light source.

The spectra were produced by a Bausch and Lomb 1.5-meter spectrograph, using a grating blazed at 7000A with a dispersion of 20 A/mm in the region of interest. A plate holder designed by Dr. A. B. Meinel has been substituted for the film holder supplied with the spectrograph, permitting the use of thin plates curved to fit the focal surface of the grating. A list of the plates obtained for this study is given in Table 1.

TABLE 1
LABORATORY SPECTRA OF GASES

Plate No.	Gas	Equivalent Path Length	Emulsion *
67	C ₂ H ₄	8 m atm	I-N
74	CH ₄	400	I-Mh
77	CH ₄	400	I-Zh
90	NH ₃	16	I-Zh
95	NH ₃	16	I-Mh
99	C ₂ H ₆	16	I-Zh
100	C ₂ H ₄	16	I-Zh
101	CH ₃ NH ₂	16	I-Zh
102	CH ₃ NH ₂	8	I-Zh
103	C ₂ H ₆	8	I-Zh

*h = hypersensitized with ammonia solution.

TABLE 2
SPECTRA OF JUPITER

Plate No.	Dispersion	Wavelength Range	Emulsion	Exposure	Date
D520	9.8 A/mm	6600-8800 A	I-Nh	240 ^m	Jan. 24, 1954
D521	35.9	8700-9720	I-Mh	145	Jan. 24, 1954
D522 *	35.9	7200-9950	I-Mh	45	Jan. 24, 1954
1169	71	9700-11200	I-Zh	360	Feb. 11, 1955

* Lunar spectrum for comparison.

The laboratory spectra were compared with spectra of Jupiter and the moon made available by Dr. G. P. Kuiper. The four plates used in this work are described in Table 2. Plate D520 is included for the discussion of abundances even though it does not overlap the region of the spectrum chosen for particular study in this paper. The long-wavelength limit of the present analysis is set by the characteristics of the laboratory spectrograph which prevent the study of the spectrum beyond 1.01 μ without considerable adjustment. The 9000A limit marks the onset of the strong 8873A band of CH₄. At shorter wavelengths, Jovian spectra of much higher dispersion (such as plate D520) are available and will be analyzed in greater detail in subsequent reports. Laboratory spectra covering the region 1.01-1.12 μ are being obtained at the present time and will be discussed in Part II of this series.

3. Identifications

Since methane and ammonia are both known to be present in the Jovian atmosphere, these gases were investigated first. It became apparent almost immediately that the strong absorptions in the region

9700-10,100A were nearly all due to methane. This is made clear in Plate 29.1 which shows the laboratory spectrum of methane compared with plate 1169 of Jupiter. Since the dispersion achieved in the laboratory is considerably higher than that used at the telescope, a larger number of bands is visible in the laboratory methane spectrum than appears in the spectrum of Jupiter. The comparison is also hindered by the difference in the manner of formation of the absorption lines in the two cases which leads to differences in their relative intensities. Nevertheless, the presence of the strong features at 9706A, 9884A, and 9985A in both spectra, together with the large number of other coincidences, makes the identification of those features appearing in both spectra quite definite. A possible exception is provided by the band at 10,048A which is obviously much stronger in Jupiter than the weak line appearing in the laboratory spectrum. This difference is partly a result of the low contrast of the laboratory plate in this region, but is also due to the intensity differences referred to above. In addition, the strong Fraunhofer line at 10,049A (Paschen 7 of hydrogen) will contribute to the 10,048A absorption in the

spectrum of Jupiter. The ammonia spectrum reveals a large number of lines in the region 9770-10,100A, but none of these is clearly separated from the strong methane absorptions in this same wavelength interval.

The region from 9000-9775A could be studied in greater detail owing to the higher dispersion of plates D521 and D522. Although there is serious interference from the ρ band of telluric water vapor, some additional members of the 9706A band of methane are visible and give added support to the identification. This is indicated in Plate 29.2, which includes the lunar spectrum for comparison.

In the course of studying the spectrum of ammonia produced by 16 meters of this gas (for comparison with the 14 meters expected in the spectrum of Jupiter [Kuiper, 1952a]), two band systems were found which were not reported by Chao (1936), whose longest path length was 8.6 meters. Both of these systems are present in the spectrum of Jupiter, one of them falling in the region discussed here (the other will be described in a separate paper). The strongest member of this system at room temperature has a wavelength of 9320A; using the frequencies of the fundamental vibrations of the ammonia molecule given by Herzberg (1945a), one is led to the assignment $3\nu_1 + \nu_2$. As both Herzberg (1945b) and Wu (1946) have stressed, however, the complexity of the ammonia spectrum makes any such assignment uncertain, particularly in the present case where no fine-structure analysis was carried out. Wavelengths of the strongest members of this system are given in Plate 29.3 which indicates their presence in the Jovian spectrum. The large number of wavelength coincidences with telluric and solar absorptions is unfortunate, but the consequent enhancement of these features (e.g., 9293A) compared with their appearance in the lunar spectrum, as well as the presence of several unblended ammonia lines, is

quite convincing. Two apparent discrepancies are the absence of the strong line at 9320A in the Jovian spectrum and the absence of a line at 9160A in the spectrum of ammonia. The first of these is almost certainly a result of the difference in the temperatures at which the two spectra are produced, together with the proximity of this line to the strong telluric blends centered at 9317A and 9324A. The second discrepancy is probably not real since the apparent absence of this line in the lunar spectrum (which would require it to have a Jovian origin) may be the result of the obvious plate defect which occurs in this region. The absorption can then be explained as the blend of water vapor lines at 9160.1A and 9160.9A, both having intensities of 4 on the revised Rowland scale (Babcock and Moore, 1947).

4. Upper Limits

Kuiper (1952b) has given an extensive list of gases which could be considered as possible constituents of various planetary atmospheres. Many of these can be eliminated as subjects for the present investigation because of the reducing nature of the Jovian atmosphere. Of the remaining gases, those which are most likely to be present as a result of reactions of the known constituents can be selected on the basis of photochemical arguments such as those presented by Wildt (1937) and Cadle (1962), and from the experimental work of Sagan and Miller (1960). The list is further narrowed by the requirement that the gas must have at least one strong absorption band in the region of the spectrum being studied which is visible at the dispersions employed — this requirement has been relaxed to permit the inclusion of C_2H_4 and HD. We are left with six gases for which data were either obtained in the present investigation or are available from other sources. These are listed in Table 3 and discussed below. The limits given in the table are intended as a first approximation only;

TABLE 3
UPPER LIMITS ON THE ABUNDANCES OF SIX GASES IN
THE JOVIAN ATMOSPHERE

Gas	Band Used	Abundance Limit	Comparison Plate
CH_3NH_2	9950 A	8 m atm	1169
C_2H_4	8715	2	D520
C_2H_6	9060	4	D521
SiH_4	9738	20	D521
CH_3D	9936	30	1169
HD	} 7377 7464	500	D520

they are based on a simplified model atmosphere in which the gas is assumed to lie above a reflecting surface and to contain no particles which scatter light in the wavelength interval under consideration. Since the gases investigated were not detected, it is clear that we are dealing with weak lines which if present would have intensities corresponding very nearly to the intensities of lines produced by the path lengths used in the laboratory (van de Hulst, 1952). Additional corrections should be made for the difference in pressure and temperature between the laboratory and planetary environments. The limits presented here are based on the laboratory values of these parameters; they were not corrected to N.T.P. since the information required was not available for three of the gases. The effect of such a correction will be to lower the limits somewhat, by a factor 0.85 for the first three gases. An effective path length of two air masses has been assumed since the planet is observed as an extended disk.

Methylamine (CH_3NH_2): The 9950A band consists of several Q branches on either side of an intensity minimum. It should be noted that there is strong overlapping in this region from CH_4 ; otherwise a more sensitive determination would be possible.

Ethylene (C_2H_4): The band at 8715A consists of several members of which a broad feature centered at 8693A and two sharper absorptions at 8715A and 8724A are the strongest. The limit in the table allows for the higher dispersion used at the telescope in this case.

Ethane (C_2H_6): The 9060A band is unresolved on the laboratory plates, but causes a wide (50-100A) depression in the continuum. Such a depression was searched for without success in the spectrum of Jupiter. The limit given takes into account the slight interference caused by the 8873A band of CH_4 .

Silane (SiH_4): It is not possible to add to the discussion of Bardwell and Herzberg (1953), even though the spectrum of Jupiter available for the present study is of a higher quality than the spectra which they were able to use. This lack of precision is due to the presence of strong absorptions at 9737-38A, due both to telluric H_2O and Jovian CH_4 which require the use of very high dispersion to lower substantially the limit set by these authors.

Methyl deuteride (CH_3D): The most favorable of the absorptions listed by Bardwell and Herzberg (1953) is the one at 9936A, since it is essentially free from interference by CH_4 . This is evident from inspection of Plate 29.1, which also shows the ab-

sence of the CH_3D absorption. It is difficult to set a limit in this case since the spectrum was not shown in the original article. The maximum path length used was 90 meters, and the absorption at 9936A was classified as medium in strength. From this and the fact that Childs and Jahn (1936, 1939) apparently observed bands in this region with a path length of only 6 meters (but with much higher dispersion), it seems safe to conclude that the amount given in the table would have been visible if present.

Deuterium hydride (HD): The (3,0) rotation-vibration band of this gas falls in the wavelength region of principal interest, but consists of sharp, widely separated lines which would not be detectable at the dispersions used here. The (4,0) band occurs in the N-plate region where higher dispersion can be employed. It is assumed that the 1000 m atm path used in the laboratory by Durie and Herzberg (1960) would lead to detectable absorptions on plate D520. This assumption is supported by the fact that the intrinsically very narrow S(0) and S(1) lines of the (3,0) band of the quadrupole rotation-vibration spectrum of H_2 are visible on this plate. The wavelengths given in the table refer, respectively, to the R(0) and P(1) lines of the (4,0) band.

It is possible to set a very rough upper limit on the Jovian deuterium-hydrogen ratio from these last two results. The amount of methane present is 150 m atm. Hence we have the ratio $\text{CH}_3\text{D}/\text{CH}_4 < 1/5$. This leads in turn to the ratio $\text{D}/\text{H} < 1/23$. HD provides a more sensitive test, leading to a ratio of $\text{D}/\text{H} < 1/100$ if the 27 km atm abundance of molecular hydrogen given by Spinrad and Trafton (to be published) is adopted. This is still almost two orders of magnitude greater than the terrestrial ratio of $1/6400$ which would allow only $1/5$ m atm of CH_3D and 17 m atm of HD in the optical path which produces the Jovian spectrum. It is clear that only very-high dispersion spectra and considerable deuterium enrichment would permit these gases to be detected in this part of the spectrum. Kuiper (1952c) has suggested that enrichment could have occurred if there was a sufficient interval of time in the planet's early history when H_2 could just escape from the atmosphere while the escape of HD was negligible. At the moment, the best hope for lowering this crude abundance limit would seem to be furnished by the possibility of observing farther in the infrared where smaller quantities of both gases produce detectable absorptions. The limiting factor in such work will probably be the extensive overlapping of the strong CH_4 and NH_3 absorption bands which occur in this

spectral region.

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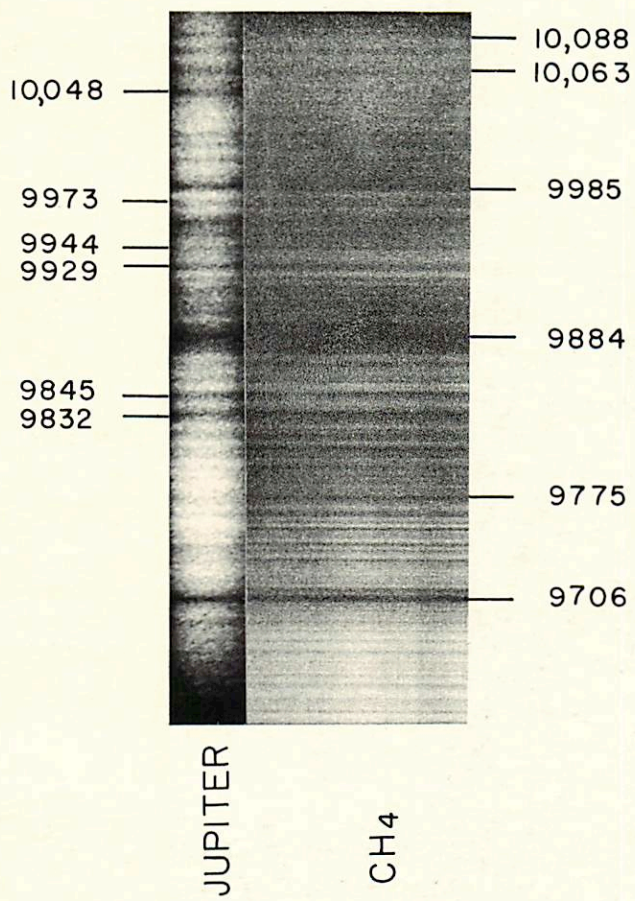


Plate 29.1.—Spectra of Jupiter and methane, 9630-10,100A.

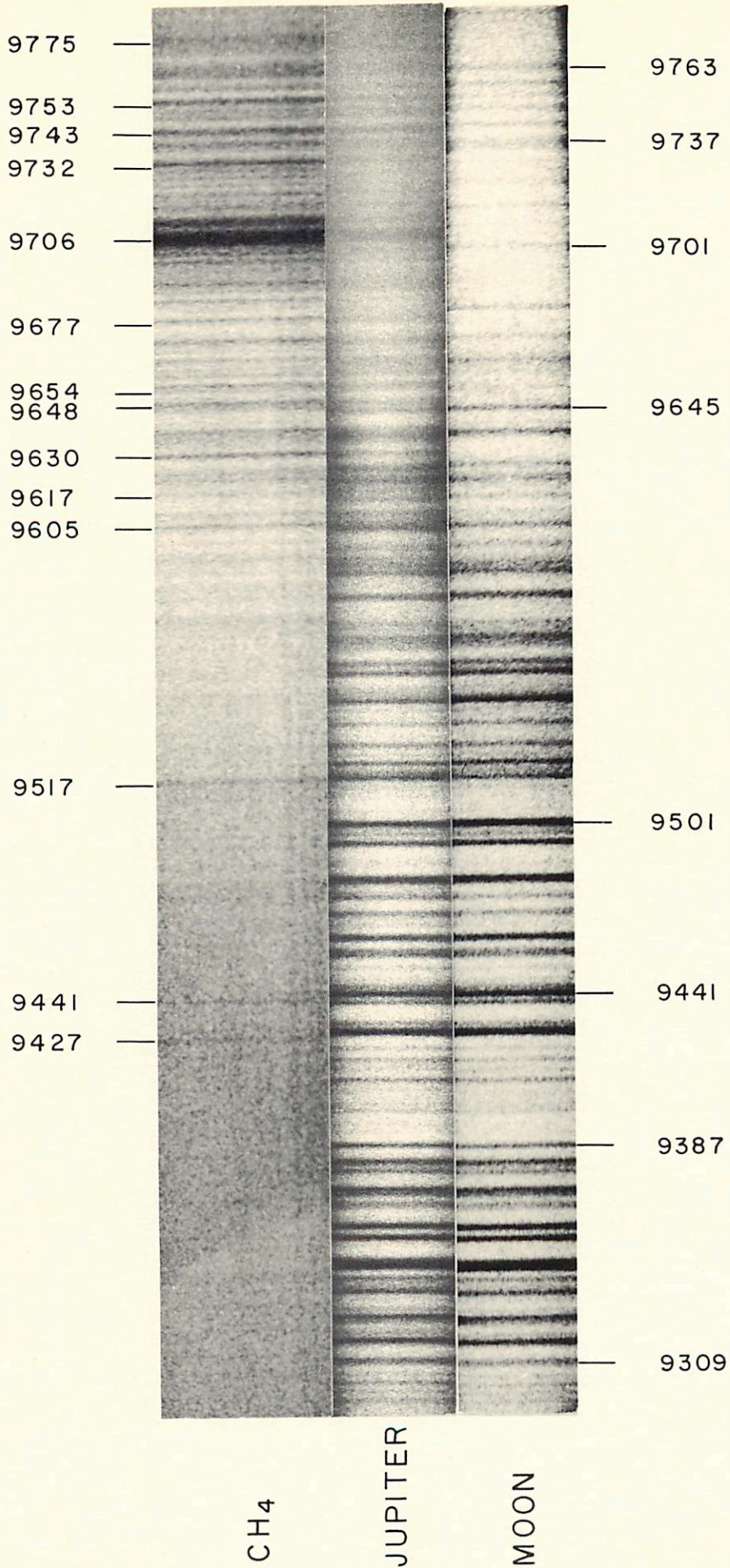


Plate 29.2.—Spectra of methane, Jupiter, and the moon, 9300-9775A.

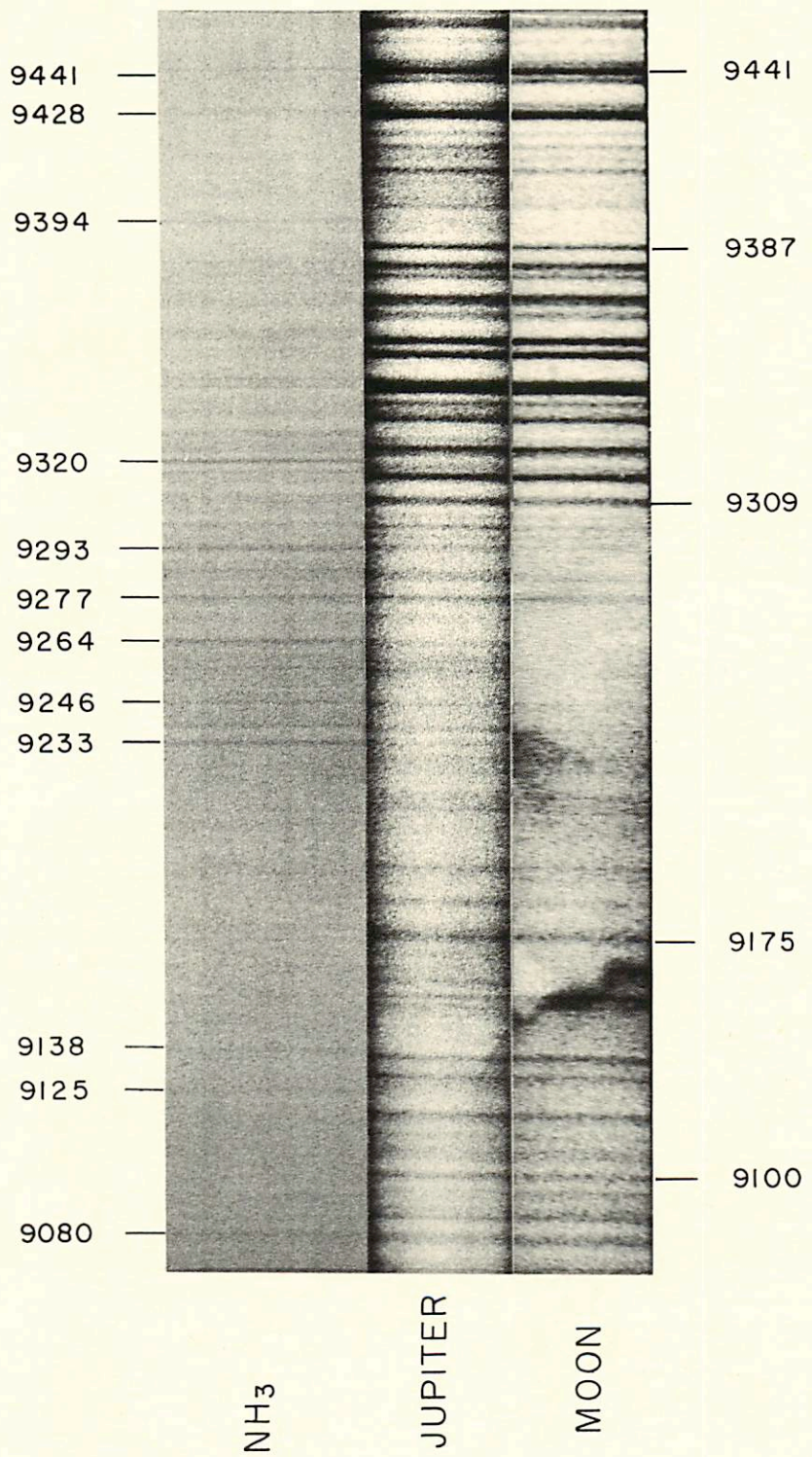


Plate 29.3.—Spectra of ammonia, Jupiter, and the moon, 9080-9455A.

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