

No. 103 THE INFRARED SPECTRUM OF JUPITER, 0.95–1.60 MICRONS,  
WITH LABORATORY CALIBRATIONS

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ABSTRACT

New spectra of Jupiter in the region 0.95–1.60 microns are presented with calibrations from laboratory studies of the bands of  $\text{CH}_4$  and  $\text{NH}_3$ . Estimates of the quantities of these gases above the effective reflecting layer in the Jupiter atmosphere are given for each of several individual bands. The presence of  $\text{C}_2\text{H}_2$ ,  $\text{H}_2\text{S}$ , and  $\text{HCN}$  is investigated with the aid of composite spectra of these gases in addition to  $\text{CH}_4$  and  $\text{NH}_3$ . We find as upper limits 8 cm-atm for  $\text{C}_2\text{H}_2$ , 50 cm-atm for  $\text{H}_2\text{S}$ , and 10 cm-atm for  $\text{HCN}$ .

*1. Introduction*

On January 5, 1967, we obtained infrared spectra of Jupiter in the range 0.95–1.60  $\mu$ , having higher resolution than those previously published by Kuiper (1964) and Moroz (1966). Because the higher resolution increases the opportunity to search for minor constituents in the Jupiter atmosphere, and to study the absorption characteristics of different bands, these new spectra are presented with laboratory spectra of different amounts of methane, ammonia, acetylene, hydrogen sulfide, and hydrogen cyanide, at a resolution commensurate with the Jupiter spectra. The spectra of Jupiter given here have a resolution  $\lambda/\Delta\lambda \approx 700$  at 1.5  $\mu$ , while the apparent

resolution of Moroz' tracings is 250 and that of Kuiper's 450.

*2. The Spectrum of Jupiter*

Three tracings of the spectrum of Jupiter were obtained with the infrared spectrometer described by Kuiper, et al. (1962) and the 61-inch NASA reflector of the Lunar and Planetary Laboratory. A lead sulfide detector of width 1.0 mm was used with an entrance slit of 1.0 mm (subtended angle 10 seconds of arc). The slit was aligned roughly parallel to the equator and included the equatorial zone and parts of the north and south equatorial belt. The spectrum was scanned at 1.72  $\text{\AA}/\text{sec}$  with a time constant of 10 sec. The three tracings were averaged and a hand-drawn composite prepared. The composite and the two best individual spectra are presented in Figures 1 through 3.

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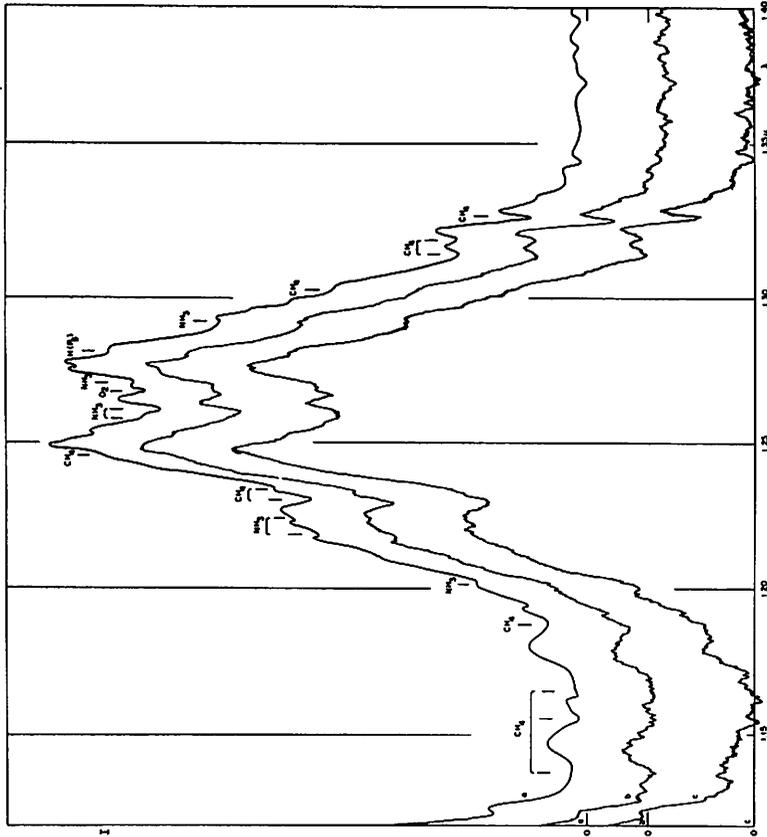


Fig. 2 Spectrum of Jupiter, Part 2, 1.12-1.40  $\mu$ ; as Fig. 1.

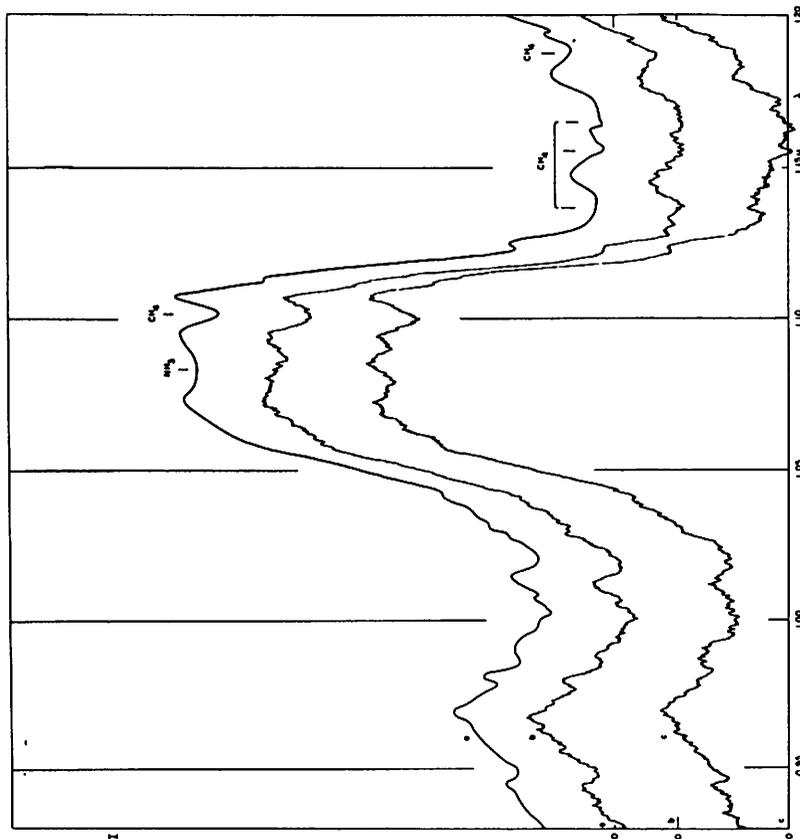


Fig. 1 Infrared spectrum of Jupiter, Part 1, 0.93-1.20  $\mu$ . Curve *a* is a composite of tracings *b* and *c* and a third, not reproduced. Band identifications are taken from laboratory spectra. The spectrum up to 1.12  $\mu$  can be observed with higher resolution by photographic spectroscopy.

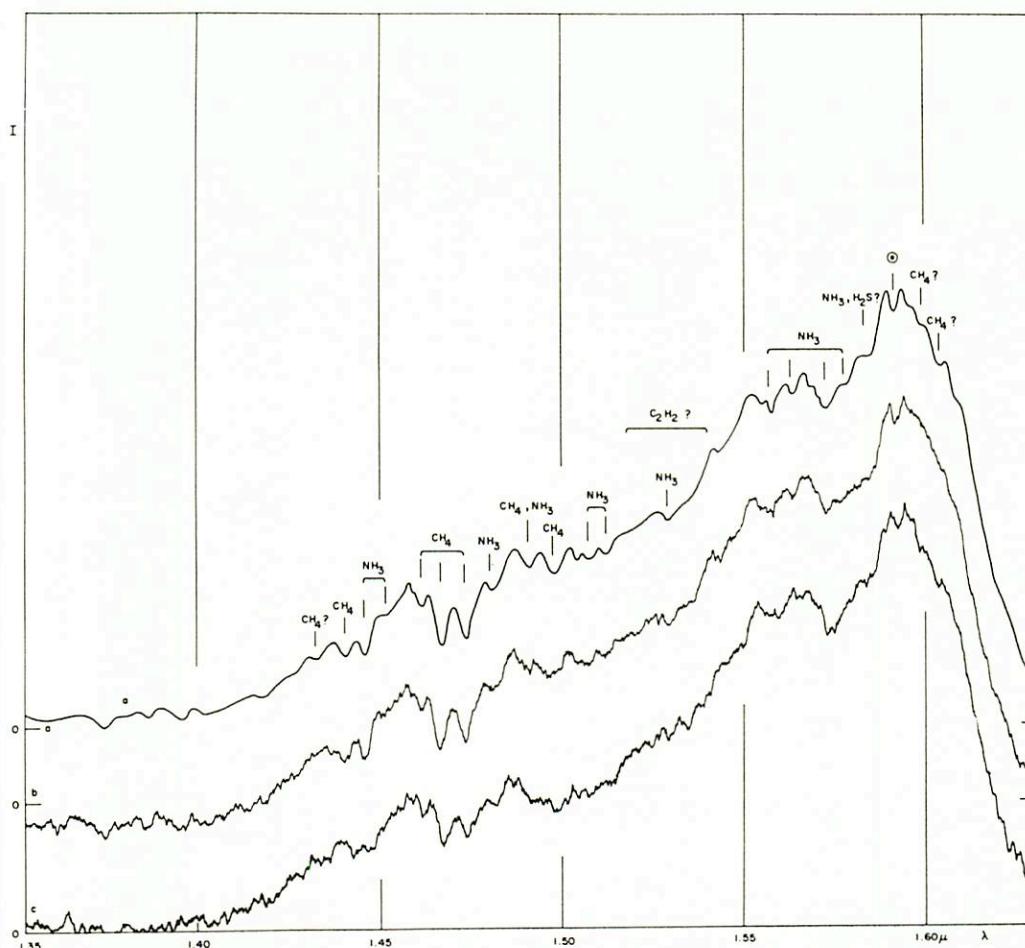


Fig. 3 Spectrum of Jupiter, Part 3, 1.35–1.63  $\mu$ ; as Fig. 1.

### 3. Laboratory Comparisons

In 1964, Kuiper published a series of laboratory spectra of different amounts of  $\text{CH}_4$  and  $\text{NH}_3$  with a resolution comparable to his spectrum of Jupiter. We have similarly prepared a series of these spectra with slightly higher resolution to correspond more closely to the spectra of Jupiter in Figures 1–3. A single pass absorption tube of length 40 meters with quartz windows and a quartz-iodine lamp was used. To increase the amount of gas in the path, it was necessary to increase the pressure; the effects of band growth shown in Figures 4–9 are not pressure independent. Figures 4–6 show tracings of different amounts of  $\text{CH}_4$  within the wavelength interval 0.93–1.72  $\mu$ . The best overall fit to the Jupiter spectrum corresponds to approximately 56 m-atm  $\text{CH}_4$  at 1.4 atm pressure. With this quantity of methane in the absorption tube, we added increasing amounts of  $\text{NH}_3$  so that the gases were mixed inside the tube.

The spectra so obtained are shown in Figures 7–9. The composite spectrum of  $\text{NH}_3$  and  $\text{CH}_4$  is more easily compared to the spectrum of Jupiter than are spectra of the individual gases alone. Using these laboratory data we have attempted to identify the prominent features in the Jupiter spectrum, the results of which are indicated above the composite tracing in Figures 1–3. Several uncertainties remain in the identification and such features are indicated with a question mark.

Using the laboratory observations of  $\text{CH}_4$  and  $\text{NH}_3$ , we have estimated the approximate equivalent absorbing pathlength above the scattering/reflecting layer in the Jupiter atmosphere for several different absorption bands. The estimates are given in Table 1. Because the laboratory observations were made with a single fixed-pathlength absorption cell, the observed band-development with increasing amounts of gas is not pressure independent. Further, our observations

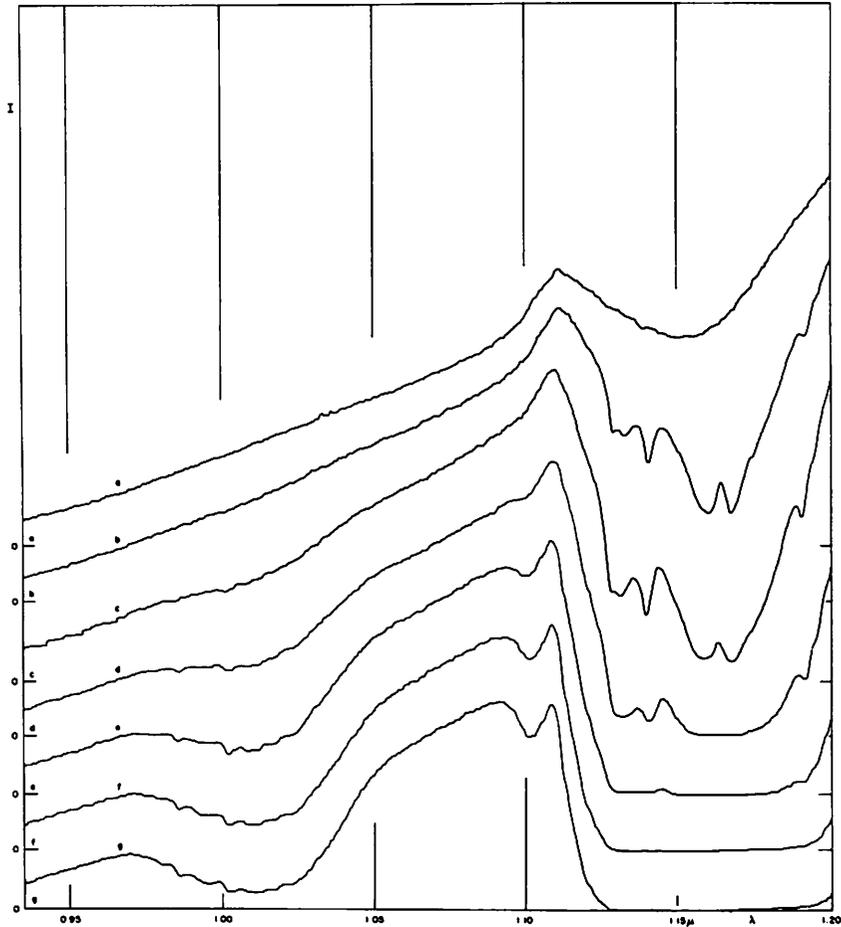


Fig. 4 Spectra of increasing amounts of  $\text{CH}_4$ , Part 1, 0.94–1.20  $\mu$ . In all spectra, the absorbing path length is 40 m. Curve *a* is a blank run with absorption tube evacuated, but with 3 m air path in spectrometer (about 18 microns precipitable  $\text{H}_2\text{O}$ ). All spectra in Figures 4–11 have same spectrometer air path. Curve *b*, 5.26 m-atm  $\text{CH}_4$  at 0.132 atm pressure; *c*, 17.38 m-atm  $\text{CH}_4$  at 0.434 atm pressure; *d*, 36.8 m-atm  $\text{CH}_4$  at 0.93 atm pressure; *e*, 76.8 m-atm  $\text{CH}_4$  at 1.92 atm pressure; *f*, 117.0 m-atm  $\text{CH}_4$  at 2.92 atm pressure; *g*, 156.8 m-atm  $\text{CH}_4$  at 3.92 atm pressure.

were all made at room temperature ( $22^\circ\text{C}$ ) so that the appearance of the bands and the adjacent continuum may differ somewhat from those in the spectrum of Jupiter. The effects of temperature and/or pressure are especially evident in the  $\text{NH}_3$  band at 1.255  $\mu$  wherein the two minima are reversed in relative intensity in the laboratory spectra, and in the  $\text{CH}_4$  band at 1.31  $\mu$ , which is much weaker in the Jupiter spectrum than in the laboratory runs. The estimates in Table 1 are correct in the first approximation, but to higher accuracy must be understood as relative only to our laboratory data. There may be errors by as much as a factor of two, especially for the strong bands which, in the case of Jupiter, may form high in the planet's atmosphere where the pressure is less by a factor of 3 or more than that in the laboratory.

The wide range of values for  $\text{CH}_4$  and  $\text{NH}_3$  in Table 1 attest to the often neglected fact that a reliable estimate of the quantity of either of these gases cannot be made from the study of a single band. As Kuiper (1952, 1964) and others have pointed out, one must recall that strong bands reach absorption at much higher levels in the atmosphere than do weak ones.

It can be seen from Table 1 and the figures illustrating the ammonia bands that  $\text{NH}_3$  is an important absorbing molecule in the Jupiter atmosphere. Danielson (1966 p.955) reached the opposite conclusion because his Stratoscope II spectra showed an intensity maximum instead of a depression at  $1.53 \pm 0.02 \mu$ , very near the 1.51  $\mu$  band of  $\text{NH}_3$ . This is purely an effect of the low resolution of the Stratoscope II spectra. It can be seen in Figure 3 that the "window"

TABLE I

Prominent bands of CH<sub>4</sub> and NH<sub>3</sub> identified in the spectrum of Jupiter with estimates of the equivalent amount of gas giving the same absorption in laboratory conditions.

MOLECULE	WAVELENGTH (μ)	EQUIVALENT AMOUNT ABOVE JUPITER CLOUD LAYER
NH <sub>3</sub>	1.08	5 m-atm
CH <sub>4</sub>	1.10	100
NH <sub>3</sub>	1.22	0.8
CH <sub>4</sub>	1.23	100
NH <sub>3</sub>	1.26	2
NH <sub>3</sub>	1.29	0.8
CH <sub>4</sub>	1.31-1.32	25
CH <sub>4</sub>	1.33	13
CH <sub>4</sub>	1.44	10-20
CH <sub>4</sub>	1.47	20-60
NH <sub>3</sub>	1.51	0.2
NH <sub>3</sub>	1.53	0.2
NH <sub>3</sub>	1.57	4

in the Jupiter atmosphere from 1.40-1.63 μ is strongly asymmetrical with the intensity peak at 1.59±0.01 μ. Danielson's spectra smear out this window to a nearly symmetrical envelope with the peak shifted to shorter wavelengths. The asymmetry

shown in our spectra is also well displayed in the records of Kuiper (1964) and Moroz (1966). The importance of telluric water vapor in shaping this envelope is small compared to that of CH<sub>4</sub> and NH<sub>3</sub>. The H<sub>2</sub>O band closest to the region of interest is the relatively narrow absorption (at this resolution) at 1.47 μ. Comparison of a spectrum of the moon made when the telluric water vapor concentration was similar to that when the Jupiter records were made (for example, Kuiper, 1964, Figure 11) shows that the intensity at the deepest part of the band is about 70 percent of the intensity at 1.59 μ. In the Jupiter spectrum in Figure 3, the intensity at 1.47 μ is 25 percent of the peak at 1.59 μ. This illustrates that water vapor absorption in this region does not account for the discrepancy between the spectra of Danielson and those of Kuiper, Moroz, and the present authors.

Danielson (1966, p.955 and note added in proof) correctly concluded that the broad, deep absorption

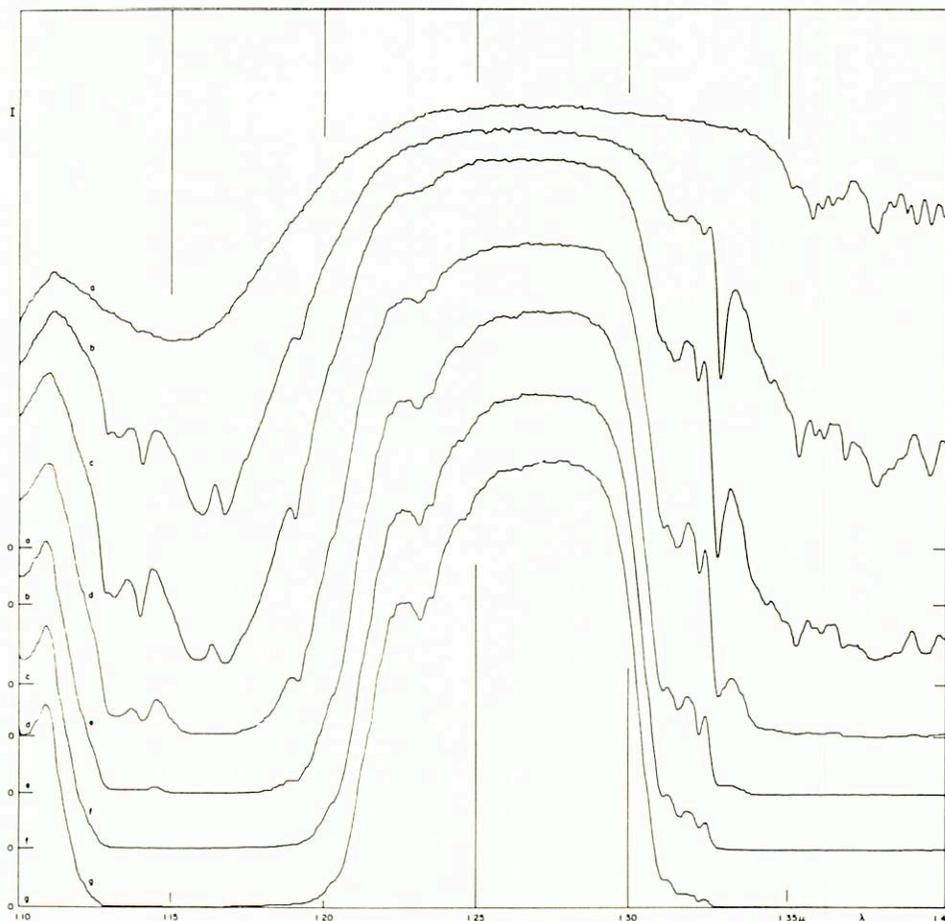


Fig. 5 Spectra of CH<sub>4</sub>, Part 2, 1.10-1.40 μ; as Fig. 4.

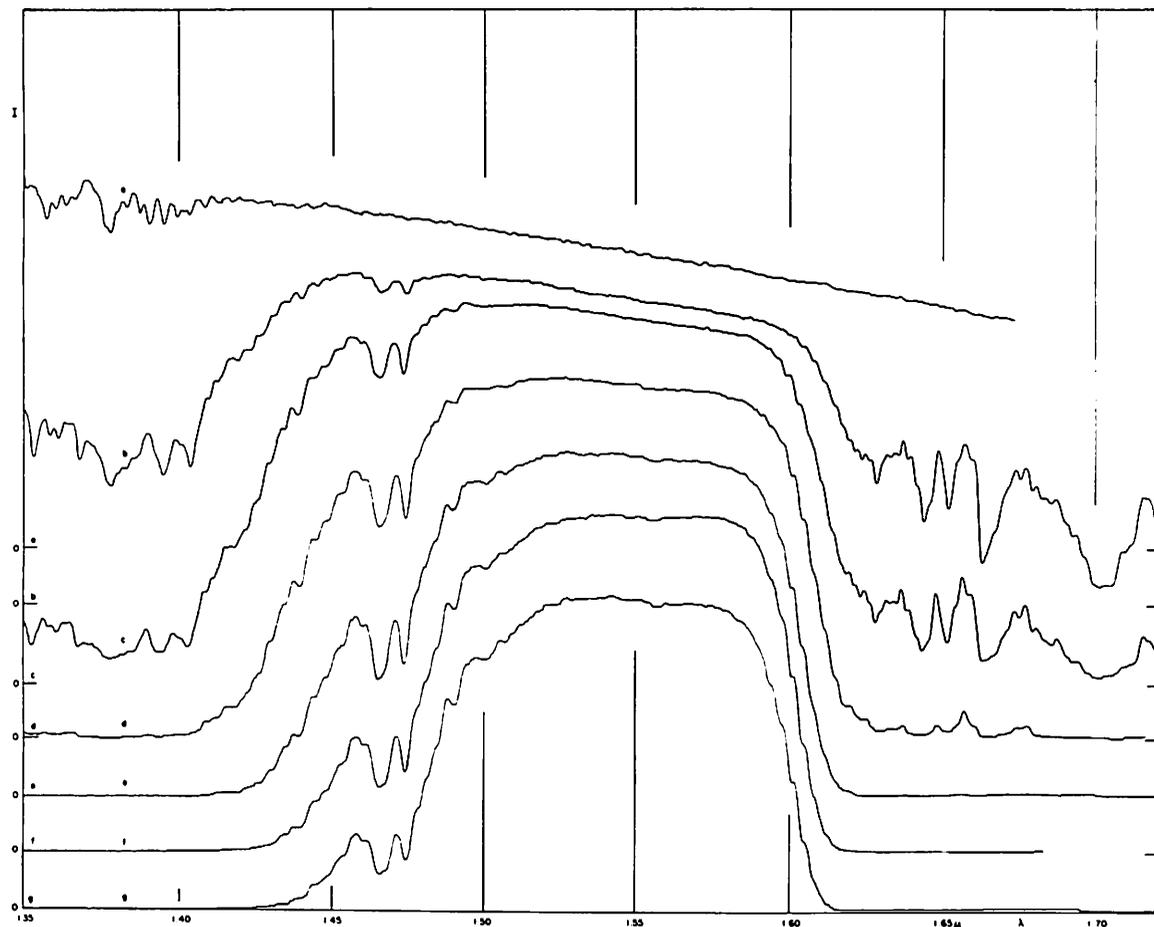


Fig. 6 Spectra of  $\text{CH}_4$ , Part 3, 1.35–1.72  $\mu$ ; as Fig. 4.

at 1.37  $\mu$  is caused by  $\text{CH}_4$ . This is evident in Figures 5 and 6 where the growth of the band superimposed on the small water vapor absorption in the laboratory (corresponding to 18 microns precipitable  $\text{H}_2\text{O}$ ), is well shown. These spectra are offered in lieu of those of Owen and Cruikshank (unpublished) mentioned by Danielson (1966, p.959).

Mention must be made also of Danielson's discussion of the absorptions at 1.15  $\mu$ . He indicates that if a significant fraction of the absorption there is due to the 2–0 band of  $\text{H}_2$ , the depth of the bands corresponds to approximately 45 km-atm  $\text{H}_2$  for a temperature of 200–225°K. By comparing Figures 2 and 4, it can be seen that the three individual minima at about 1.135  $\mu$  (broad), 1.155  $\mu$ , and 1.165  $\mu$  correspond in detail to features of  $\text{CH}_4$ . From these room temperature comparisons, the 1.135  $\mu$  band is most closely matched by 36.8 m-atm  $\text{CH}_4$  at 0.93 atm pressure, while the latter two bands agree well with 17.4 m-atm  $\text{CH}_4$  at 0.434 atm pressure. Contributions from the relatively weak telluric

$\text{H}_2\text{O}$  band at 1.13  $\mu$  are insignificant. If then, as it seems, much of the absorption in the 1.15  $\mu$  region is due to  $\text{CH}_4$ , Danielson's estimate of the amount of  $\text{H}_2$  in the absorbing path is too great, making the abundance in this band more nearly in accord with that of about 14 km-atm estimated from the  $\text{H}_2$  absorptions near 2.25  $\mu$  (see Appendix).

#### 4. Acetylene, Hydrogen Sulfide, and Hydrogen Cyanide

The presence of minor constituents on Jupiter is important to the chemical equilibrium of the atmosphere. In order to make an accurate test for the presence of  $\text{H}_2\text{S}$ ,  $\text{HCN}$ , and  $\text{C}_2\text{H}_2$ , we observed these gases against the background of absorptions of  $\text{CH}_4$  and  $\text{NH}_3$ . These three gases were considered possible contributors to the array of features in the Jupiter spectrum partly on the basis of comparisons with the laboratory spectra of Cruikshank (1967). Recognition that composite spectra are superior to single spectra for the detection of individual lines or line

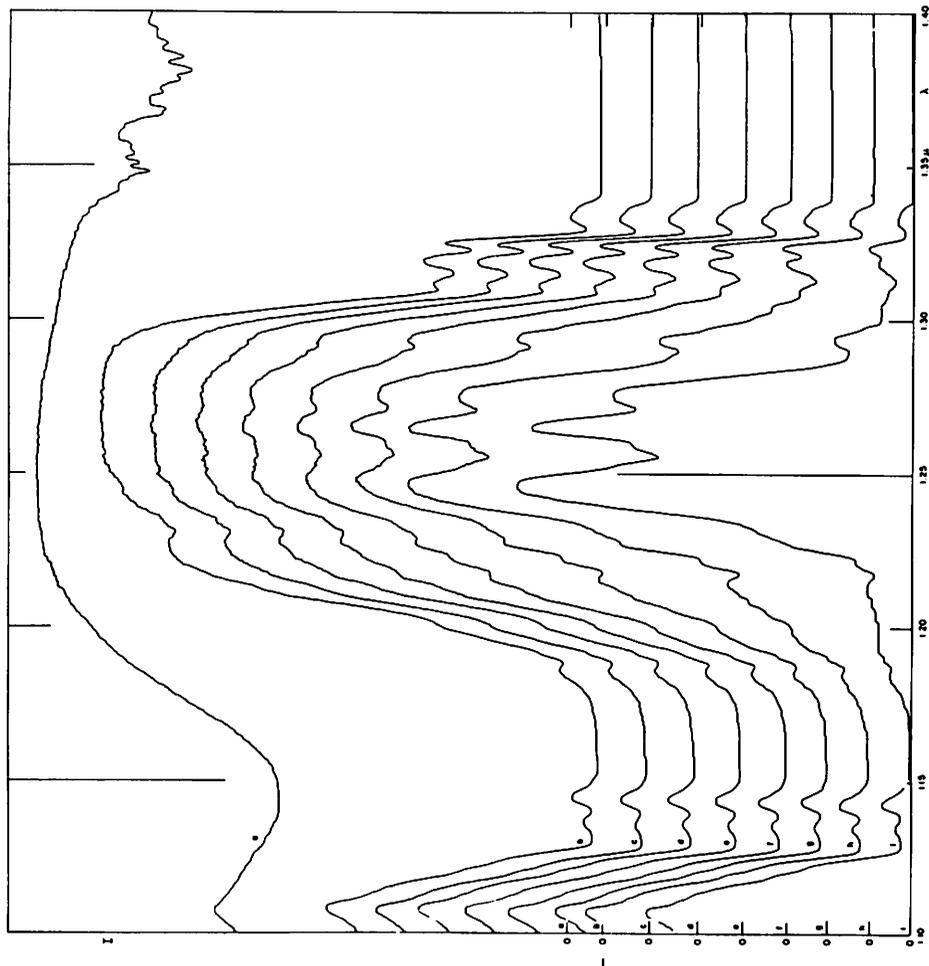


Fig. 7 Spectra of  $\text{CH}_4$ , with increasing amounts of  $\text{NH}_3$  added, Part 1, 0.93–1.20  $\mu$ . Absorbing path length is 40 m for all spectra. Curve *a* is a blank run with no gas in absorbing tube, but with 3 m air path in spectrometer (about 18 microns precipitable  $\text{H}_2\text{O}$ ). All spectra in Figures 4–11 have same spectrometer air path. Curves *b–f* have 55.6 m-atm  $\text{CH}_4$  at 1.42 atm partial pressure. Curve *b* has no  $\text{NH}_3$ ; remaining spectra have  $\text{NH}_3$  added in the following amounts with the indicated total pressure: 0.105 m-atm  $\text{NH}_3$ , 1.424 atm; *d*, 0.211 m-atm  $\text{NH}_3$ , 1.426 atm; *e*, 0.422 m-atm  $\text{NH}_3$ , 1.432 atm; *f*, 0.899 m-atm  $\text{NH}_3$ , 1.443 atm; *g*, 1.847 m-atm  $\text{NH}_3$ , 1.47 atm; *h*, 3.69 m-atm  $\text{NH}_3$  at 1.51 atm; *i*, 7.91 m-atm  $\text{NH}_3$ , 1.62 atm.

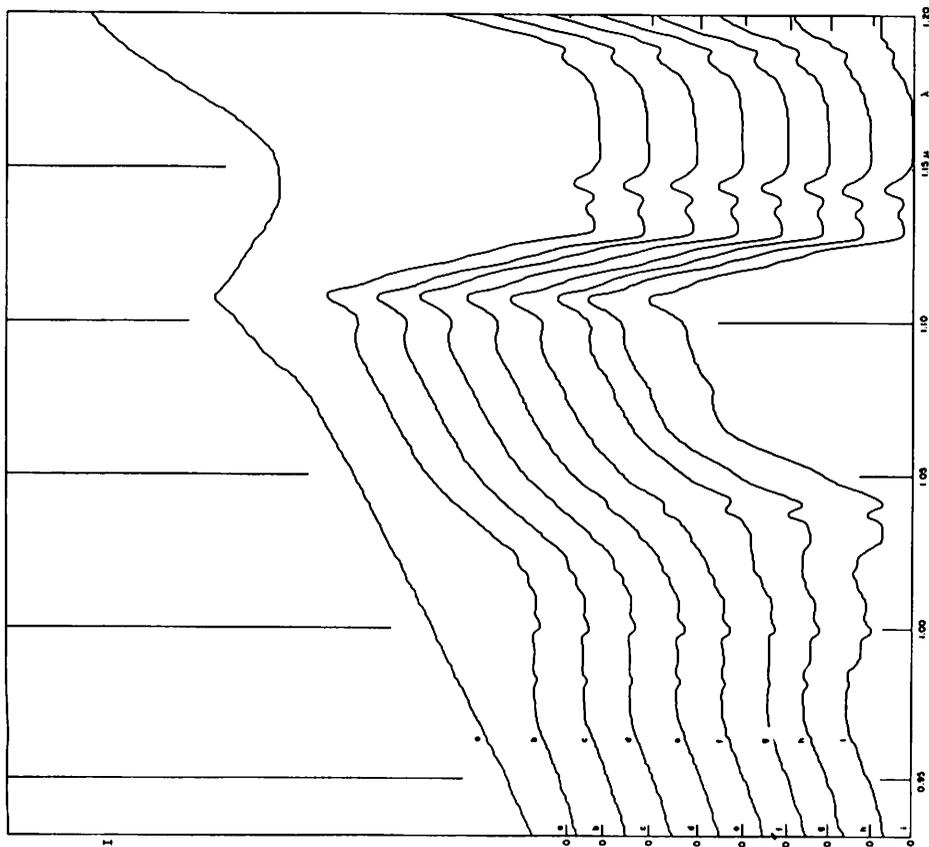


Fig. 8 Spectra of  $\text{CH}_4$ , with increasing amounts of  $\text{NH}_3$  added, Part 2, 1.10–1.40  $\mu$ ; as Fig. 7.

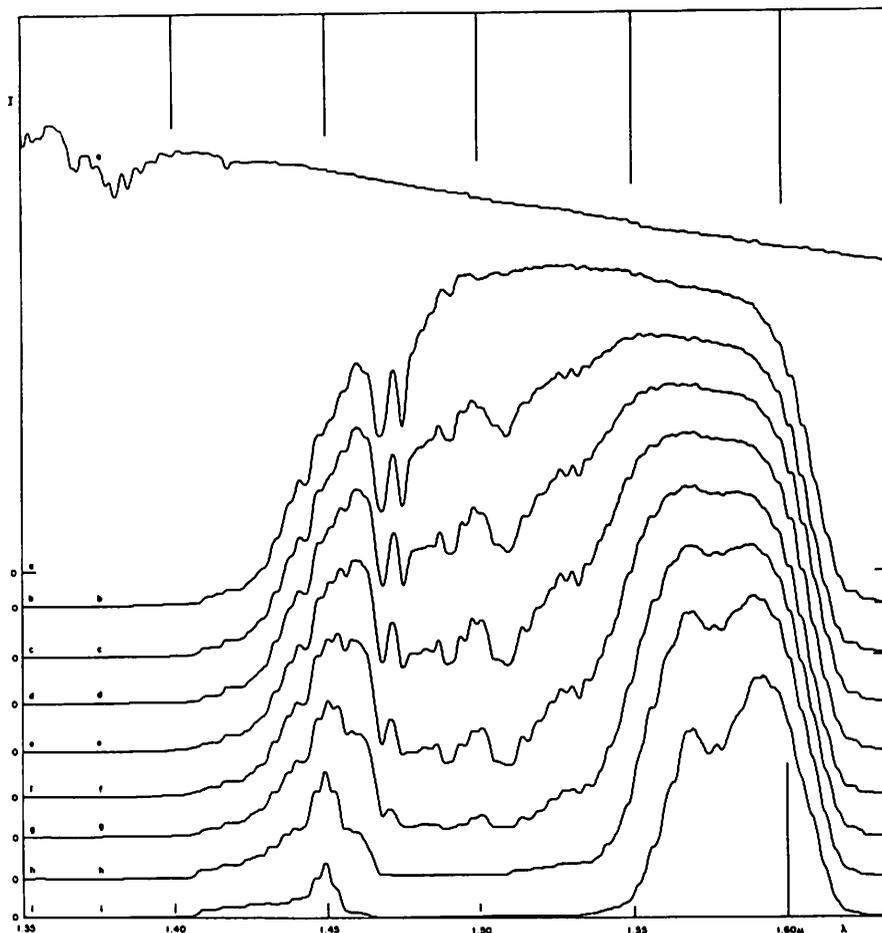


Fig. 9 Spectra of  $\text{CH}_4$  with increasing amounts of  $\text{NH}_3$  added, Part 3, 1.35–1.63  $\mu$ ; as Fig. 7.

blends supported the use of the following laboratory procedure.

The single-pass 40-meter absorption tube of the Lunar and Planetary Laboratory was filled with 55.6 m-atm  $\text{CH}_4$  plus 0.211 m-atm  $\text{NH}_3$  at a total pressure of 1.4 atm. Because of the small amounts of  $\text{C}_2\text{H}_2$  required, it was not possible to introduce the gas directly into the tube with  $\text{CH}_4$  and  $\text{NH}_3$ . Thus, a 20-cm glass absorption tube with plane glass windows containing the  $\text{C}_2\text{H}_2$  was varied independently for the different amounts shown in Figure 10. There are no identifiable lines of  $\text{C}_2\text{H}_2$  in the Jupiter spectrum, but in the region of 1.51–1.55  $\mu$  where  $\text{C}_2\text{H}_2$  absorbs, the Jupiter profile is concave. In the laboratory runs with  $\text{CH}_4$  and  $\text{NH}_3$  alone, this region is convex. The absorption by about 5 cm-atm  $\text{C}_2\text{H}_2$  changes the profile to match more nearly that of Jupiter. It must be understood, however, that effects of temperature and/or pressure discussed above may account for the concave  $\text{CH}_4$ - $\text{NH}_3$  profile in Jupiter,

and the identification of  $\text{C}_2\text{H}_2$  must be regarded only as a possibility. Owen (1965) used the 10372 Å band of  $\text{C}_2\text{H}_2$  to establish an upper limit of 3 m-atm of this gas in the Jupiter atmosphere. Using the stronger infrared absorptions, in particular the 101 band at 1.538  $\mu$  considered above, we can establish an upper limit of 8 cm-atm. While 5 cm-atm would affect the shape of the profile, as noted above, 8 cm-atm should result in recognizable absorption features at the resolution of the laboratory and Jupiter data. A positive identification is not possible from these unresolved spectra; other gases absorb in this region, for example, HCN which is discussed below. Also this region lies on the shoulder of a strong band of  $\text{NH}_3$ , and as demonstrated above, different parts of the fine structure in a given band correspond to different amounts of absorbing gas. Failure of the laboratory spectra to match the curve of growth produced in planet's atmosphere can easily effect small changes in the slopes and valleys of a band.

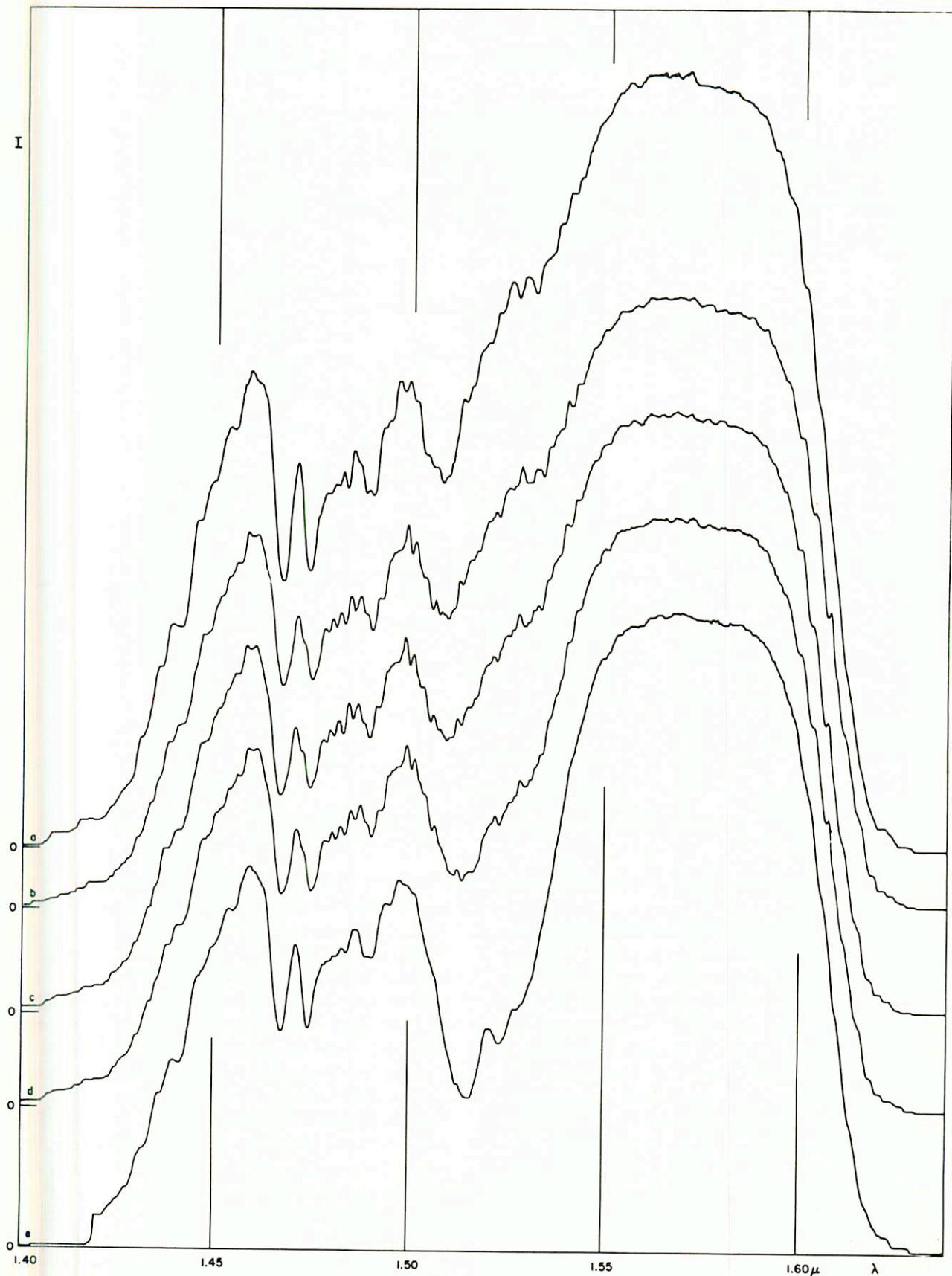


Fig. 10 Spectra of  $\text{CH}_4$ ,  $\text{NH}_3$ , and  $\text{C}_2\text{H}_2$  combined, 1.40–1.63  $\mu$ . All spectra have 55.6 m-atm  $\text{CH}_4$  plus 0.211 m-atm  $\text{NH}_3$  with path length of 40 m, total pressure 1.4 atm. Spectra *b-e* have absorptions of  $\text{C}_2\text{H}_2$  superimposed. The  $\text{C}_2\text{H}_2$  gas was contained in an absorption tube in tandem with the 40 m tube, and was used in the following amounts, always at 700 mm pressure: *b*, 2.3 cm-atm; *c*, 4.6 cm-atm; *d*, 9.3 cm-atm; *e*, 18.6 cm-atm.

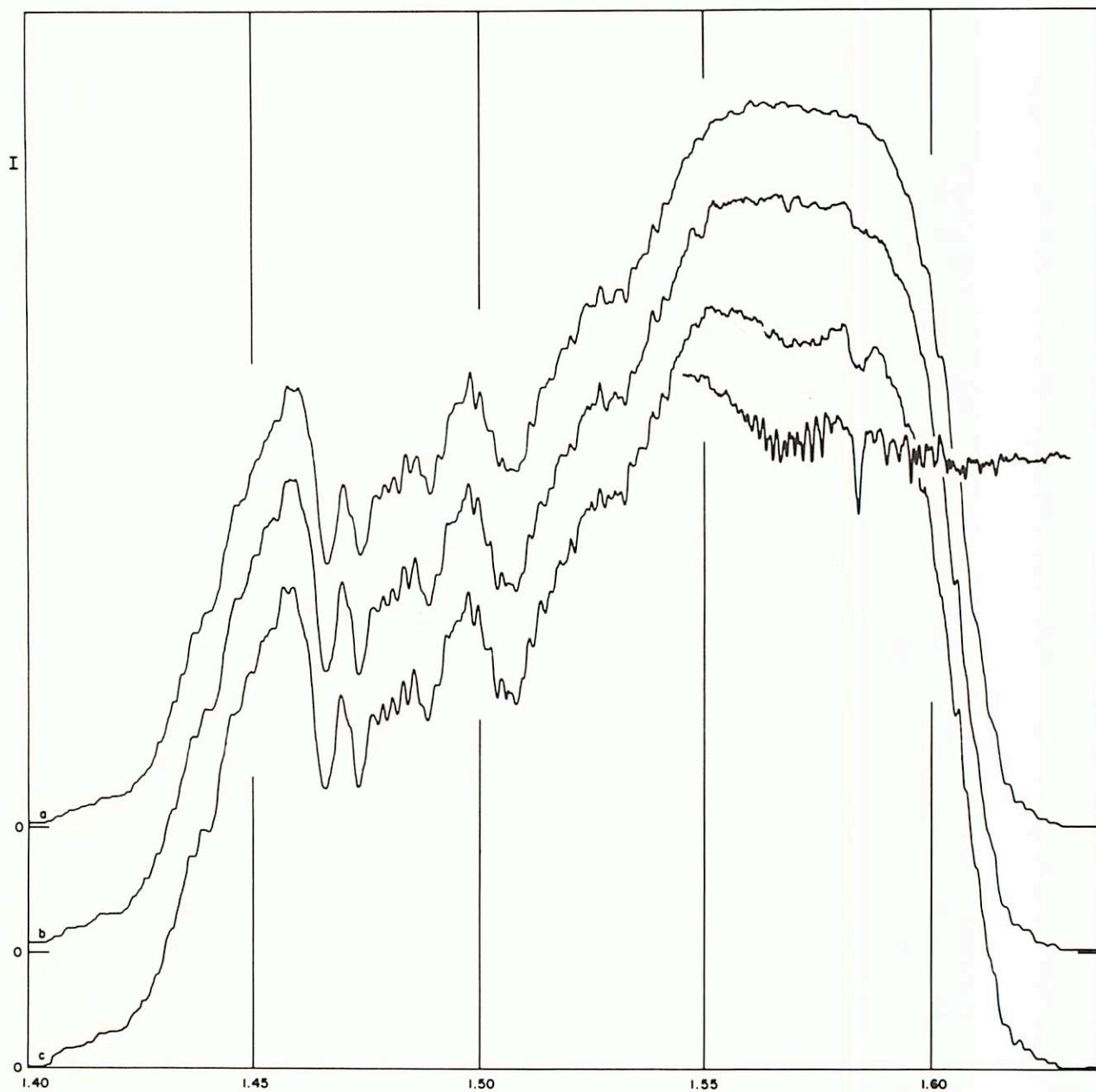


Fig. 11 Spectra of  $\text{CH}_4$ ,  $\text{NH}_3$ , and  $\text{H}_2\text{S}$  combined, 1.40–1.63  $\mu$ . All spectra were made with 40 m absorption tube and have 3 m laboratory air path in spectrometer superimposed (about 18 microns precipitable  $\text{H}_2\text{O}$ ). All spectra have 55.6 m-atm  $\text{CH}_4$  plus 0.211 m-atm  $\text{NH}_3$ . Spectrum *a* has only  $\text{CH}_4$  plus  $\text{NH}_3$ , total pressure 1.40 atm; *b*,  $\text{CH}_4$  plus  $\text{NH}_3$ , plus 0.211 m-atm  $\text{H}_2\text{S}$ , total pressure 1.403 atm; *c*, same as *b*, but with 0.632 m-atm  $\text{H}_2\text{S}$ , total pressure 1.415 atm. Small segment of  $\text{H}_2\text{S}$  spectrum inserted has only 0.65 m-atm  $\text{H}_2\text{S}$  at pressure 0.93 atm, shown at higher resolution.

Hydrogen cyanide (HCN) was observed in three different amounts for comparison with the spectrum of Jupiter. Figure 12 shows the 002 band at  $1.533 \mu$ ; there is an indication of incipient rotational structure in the P branch, just beyond the spectral resolution limit. Using the HCN cells in tandem with the 40 m tube containing  $\text{CH}_4$  and  $\text{NH}_3$ , the composite spectra in Figure 13 were made with the resolution adjusted to compare with that of the Jupiter spectra in Figures 1-3. The P and R branches of HCN are easily distinguished from the background of methane and ammonia absorptions even for 20 cm-atm of the gas. We estimate that 10 cm-atm in the double-transmission path in the Jupiter atmosphere would be visible in the Jupiter spectrum in Figure 3. This represents an improvement of a factor of 20 over the upper limit determined by Owen (1965).

A similar search was made for  $\text{H}_2\text{S}$ . This is a weakly absorbing gas, thus requiring large amounts.  $\text{H}_2\text{S}$  was therefore added directly to the tube containing 55.6 m-atm  $\text{CH}_4$  and 0.211 m-atm  $\text{NH}_3$ . The resulting spectra are given in Figure 11 with a high resolution spectrum of  $\text{H}_2\text{S}$  alone (62 cm path at pressure 705 mm Hg) added to show the band shape and partly resolved component lines. As in the case of  $\text{C}_2\text{H}_2$ , no bands could be positively identified but the laboratory spectral profile in the region  $1.58$ – $1.61 \mu$  was modified to match more closely that of the Jupiter spectra. From the spectra in Figure 11 we estimate that 0.3 m-atm  $\text{H}_2\text{S}$  could account for the shape of the Jupiter spectrum in this region, subject to the limitations of pressure and temperature noted above for acetylene. We suggest an upper limit of 0.5 m-atm for the presence of  $\text{H}_2\text{S}$  in the Jupiter spectrum (double-pass).

#### APPENDIX

In his discussion of the Jupiter spectrum in the region  $2.0$ – $2.5 \mu$ , Danielson (1966 p. 956) noted that methane absorptions alone are insufficient to account for the broad absorption between about  $2.0$  and  $2.5 \mu$ . His statement was based on the appearance of the relatively weak absorption shown in the laboratory spectra of small amounts of  $\text{CH}_4$  (Kuiper and Cruikshank, 1964). Danielson concluded that there might be absorption in this region in addition to  $\text{CH}_4$  and  $\text{NH}_3$ , and considered the collision-induced dipole transitions in  $\text{H}_2$ .

More recent laboratory studies of large amounts of  $\text{CH}_4$  have shown that the appearance of the  $2.0$ – $2.5 \mu$  region is considerably different from what one might expect using the laboratory spectra of Kuiper

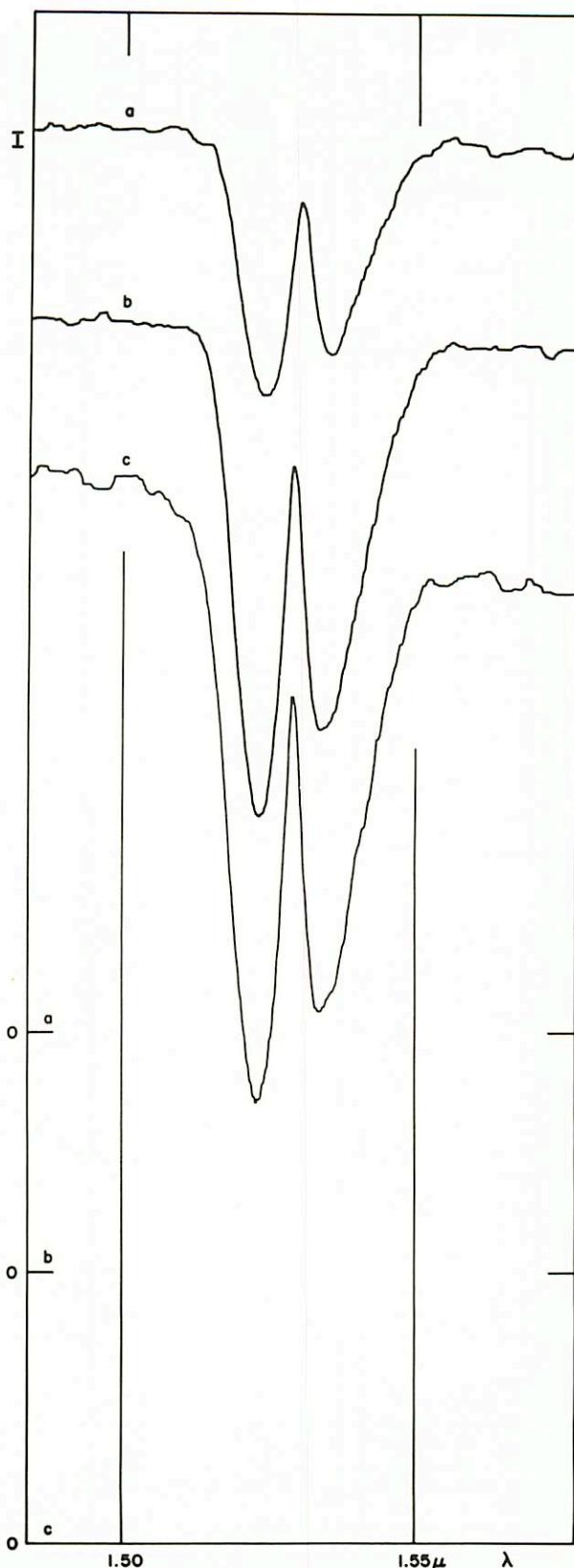
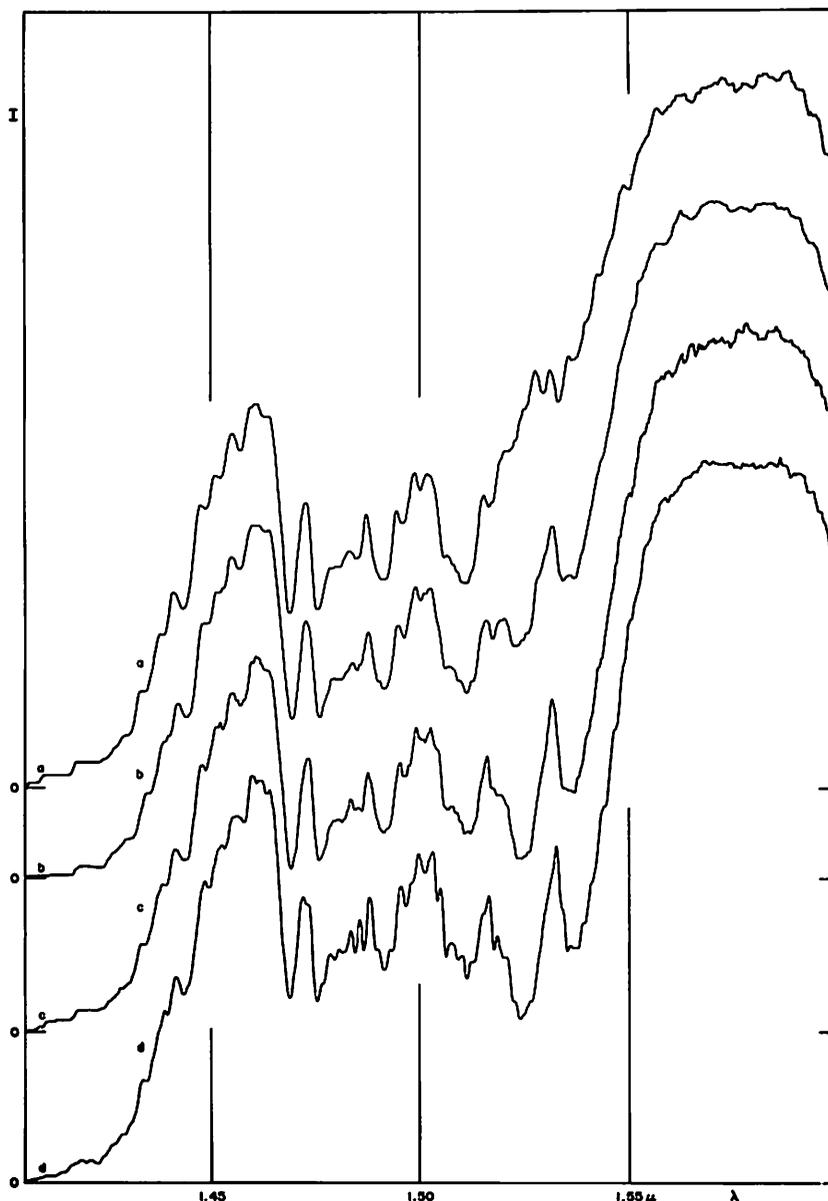


Fig. 12 Spectra of the 002 band of HCN, all at 1 atm pressure, (a) 20 cm path, (b) 38 cm path, (c) 1 m path.

and Cruikshank alone. In Figure 12 we give a family of curves showing the increase in effective band width of the  $\text{CH}_4$  absorptions as the amount of gas and pressure are increased to values more appropriate for Jupiter's atmosphere. The shortward progression of the very strong absorption terminates at about  $2.09 \mu$  for 120 m-atm  $\text{CH}_4$ . The massive absorption in this region is a blend of the 0110 ( $2.20 \mu$ ), 0011 ( $2.32 \mu$ ), and 1001 ( $2.37 \mu$ ) bands. With this amount of  $\text{CH}_4$ , the 0012 ( $1.79 \mu$ ) band also absorbs

to about  $2.04 \mu$ . As seen in Table 1, this quantity of methane is not inconsistent with some of the bands in the Jupiter spectrum. The spectra in Figure 14 do not include the effects of the strong  $\text{NH}_3$  bands at  $2.22 \mu$  and  $1.98 \mu$ , which would further alter the profile of the remaining window transmitted by the Jupiter atmosphere.

It is therefore inappropriate to draw conclusions on the abundance of hydrogen from absorptions in this spectral region where methane and ammonia



*Fig. 13* Spectra of  $\text{CH}_4$ ,  $\text{NH}_3$ , and  $\text{HCN}$  combined,  $1.40\text{--}1.60 \mu$ . All spectra have 55.2 m-atm  $\text{CH}_4$  plus 0.20 m-atm  $\text{NH}_3$  mixed in 40 m tube, at total pressure 1.39 atm.  $\text{HCN}$  contained in glass tubes external to 40 m tube. (a) no  $\text{HCN}$ , (b) 20 cm  $\text{HCN}$  at 1 atm pressure, (c) 38 cm  $\text{HCN}$  at 1 atm pressure, (d) 1 m  $\text{HCN}$  at 1 atm pressure.

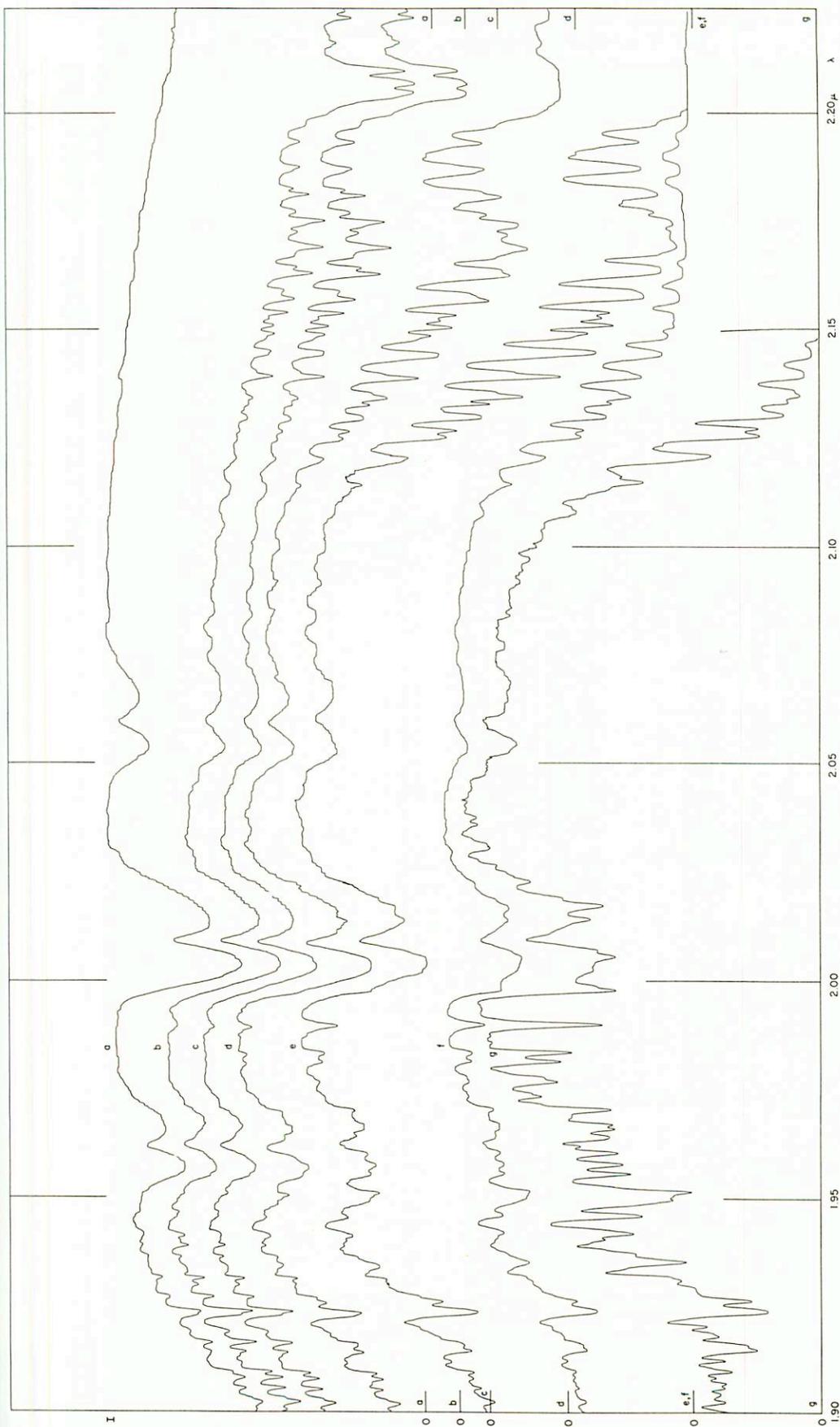


Fig. 14 Spectra of  $\text{CH}_4$ , 1.90–2.22  $\mu$ , medium resolution. All spectra were made with 40 m absorption tube and have 3 m laboratory air path in spectrometer superimposed (about 18 microns precipitable  $\text{H}_2\text{O}$ ). (a) blank run, tube evacuated, (b) 1.68 m-atm  $\text{CH}_4$ , at 0.042 atm pressure, (c) 3.37 m-atm at 0.084 atm, (d) 13.7 m-atm at 0.34 atm, (e) 26.3 m-atm at 0.66 atm, (f) 52.6 m-atm at 1.32 atm, (g) 120 m-atm at 3 atm.

bands are so strong and complexly blended, unless the resolution is much higher than that of Stratoscope II spectra or our own observations with the scanning spectrometer.

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