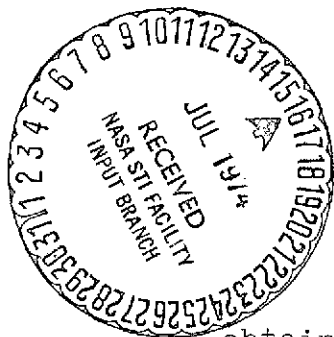


Hadamard-Transform Spectrometry of the
Atmospheres of Earth and Jupiter

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ABSTRACT

A Hadamard-transform spectrometer has been used to obtain a spectrum of Jupiter from $880\text{--}770\text{ cm}^{-1}$. Three ammonia absorption features stand out at 870, 851, and 833 cm^{-1} . The general shape of the spectrum implies an atmosphere with a monotonically decreasing temperature profile up to the 125°K level.

In addition, transmission profiles of the Earth's atmosphere were taken between 16μ and 25μ for five consecutive nights under varying amounts of atmospheric water and air mass. There are many saturated lines, but nightly variations are fairly constant and agree well with a theoretical profile.

These results show that the Hadamard-transform technique is a useful method for obtaining astronomical spectra.

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INTRODUCTION

A doubly multiplexed Hadamard-transform spectrometer has been successfully used in the laboratory by Phillips and Harwit¹. In this paper we present astronomical results obtained by the same instrument.

JUPITER OBSERVATIONS

The observations were made with the 60-inch telescope at Mt. Lemmon Infrared Observatory in May, 1972. The instrument contained three entrance slits and nineteen exit slits, with a resolution of $\Delta\lambda/\lambda \approx .004$. Each observing run consisted of measuring twenty-one spectral elements simultaneously over an 0.64 micron segment of the 11.5 μ to 13 μ band. A number of such runs were made to cover the entire band. The operation of this kind of encoding spectrometer will not be dealt with here; a full explanation is found in the literature¹⁻³.

A chopping mirror, driven at 17 Hz, produced two 22.5" x 42" beams separated by 60". The beams were positioned upon the planet with the larger dimension centered upon Jupiter's equatorial plane. Each beam subtended 0.49 of the disk areas. Radiation was collected on a copper-doped germanium detector at 4.2°K. The planet was placed in one beam and the 57 measurements required for the Hadamard-transform (cf. Harwit et al.) were made by integrating the signal for 10 seconds per measurement and storing the

results on punched paper tape. The planet was then placed in the other beam and the procedure was repeated. A spectrum was computed by taking the Hadamard-transform of one-half of the difference of corresponding points for both sets of data. A total of nineteen minutes observing was required for both spectrum pairs.

The source spectrum was corrected for telluric features by comparing it to a lunar spectrum taken on the same night by chopping between a region on the eastern limb of the moon near the equator and the adjacent sky. An intensity calibration was derived from this spectrum by assigning a temperature to the observed lunar surface from the temperature-phase relationship derived from Sinton's 11μ observations⁴. It is believed that this results in an intensity calibration for Jupiter which is accurate to $\pm 2.5^\circ\text{K}$.

The spectrum of Jupiter from 8μ to 14μ depends upon the thermal structure of its atmosphere. A spectrum by Gillett, et al.⁵, exhibited a brightness feature from 7.8μ to 8.4μ , which was interpreted as CH_4 emission from a temperature inversion in Jupiter's atmosphere. Encrenaz⁶ has computed spectra from 8μ to 14μ for various Jovian model atmospheres with and without a temperature inversion. Since the spectral structure at these wavelengths is dominated by the ν_2 band of NH_3 , he concluded that an inversion layer would result in NH_3 emission, whereas the absence of the layer would result in NH_3 absorption.

The high resolution spectrum ($\Delta\lambda/\lambda \approx .007$) of Aitken and Jones⁷, however, showed NH_3 absorption from 8μ to 13μ .

Figure 1 gives the composite spectrum for our observations from 11.5μ to 13μ . The dashed curves represent the appearance of a blackbody at various temperatures. The different symbols represent different runs. Absorption features due to the ν_2 vibration band of NH_3 are evident at 870, 851, and 833 cm^{-1} .^{6,8,9} The general shape of the spectrum resembles the model atmosphere of Encrerna for a monotonically decreasing temperature profile up to the 125°K level. The NH_3 emission expected by him from the inversion layer was not seen.

TRANSMISSION PROFILE OF THE EARTH'S ATMOSPHERE

Lunar spectra were also taken from 16μ to 25μ to measure the atmospheric transmission and its variation with water content and air mass. The lunar emission was assumed black, at temperatures derived from 11μ measurements.⁴ The spectrometer was operated in the singly-multiplexed mode³, with a spectral resolution of 0.063μ . The $7.7'' \times 42''$ beam was chopped between the eastern limb of the moon and the adjacent sky. Each element of the transform was obtained by integrating the demodulated signal for two seconds. The transform was inverted in real-time by a computer, and the data was stored on punched paper tape.

For each observing night the water content of the atmosphere was determined from radiosonde data of dew point

depressions and temperatures at various pressure levels of the atmosphere. Radiosonde readings were taken daily at 0500 and 1700 local time from Tucson International Airport. The amount of water quoted for a given date is the average of the 1700 readings of the same night and the 0500 readings the following morning. Table I lists the water content, air mass, and assumed lunar temperature for each night a spectrum was taken.

The absolute transmission was calculated by dividing the Lunar spectra by the product of the assumed lunar emission and the laboratory blackbody spectra. The results for the first four nights are shown in Fig. 2. (The complete band was not covered the first two nights as we were eager to press on to Jupiter.) The transmission features appear to be very stable from night to night, with many of the lines quite saturated. The only trend seems to be a slight decrease in the peak transmission between the lines with increasing air mass and water content, but this effect appears very weak.

The results for the final night are plotted in Fig. 3, along with a theoretical transmission spectrum calculated by Virgil Kunde¹⁰. Kunde's calculation was for a homogeneous path through 2.7 air masses containing 2 mm of precipitable water at an excitation temperature of 250°K. The calculation also included CO₂ lines. The spectrum has been smoothed to a resolution of 3 cm⁻¹ to approximate our

resolution near the center of the range.

The agreement in position, width and depth of most of the lines is rather striking. The disagreement in the peak transmissions between the lines is probably due to two false assumptions made in our data reduction and to the assumption of homogeneity in Kunde's model. Of the former, the first is that the emissivity of our 20μ -calibration blackbody was assumed to be one. Later checks, however, indicate that it may have been as low as 0.7, decreasing our calculated transmission by the same factor.

The second is that no correction was made for the fact that the effective temperatures seen at the limb of the moon are lower at any phase than those that would be seen from the center of the disk under the same illumination. This is primarily because at large angles to the vertical one sees the cooler mountain peaks, and does not see the warmer valley component. The extent of this effect is difficult to calculate, especially for the rough eastern limb. However, the effect of a lower lunar temperature on our transmission profile would be to increase the overall transmission, especially at the short wavelength end.

CONCLUSION

A doubly-multiplexed Hadamard transform spectrometer, which previously has been tested only in the lab, has now been used to obtain astronomical spectra under actual field conditions. On the basis of its field performance, and the results stated above, a more sophisticated instrument is being constructed. It will have 15 entrance and 255 exit slits with a resolution of $\Delta\lambda/\lambda \approx .001$. It will be entirely automated, and a minicomputer will perform the data collection, the transformation, and the output.

We would like to thank Prof. N. J. Woolf for making the Mt. Lemmon Infrared Observatory available to us, and Virgil Kunde for supplying us with a copy of his theoretical transmission profile of the Earth's atmosphere.

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FIGURE CAPTIONS

- Fig. 1 : Jovian Spectra. Different symbols represent different grating positions. The two sets of triangles represent spectra taken at different times.
- Fig. 2 : Atmospheric transmission profiles for four consecutive nights.
- Fig. 3 : Comparison between experimental and theoretical transmission profiles. Smooth curve = theoretical results. Dashed lines = experimental data.

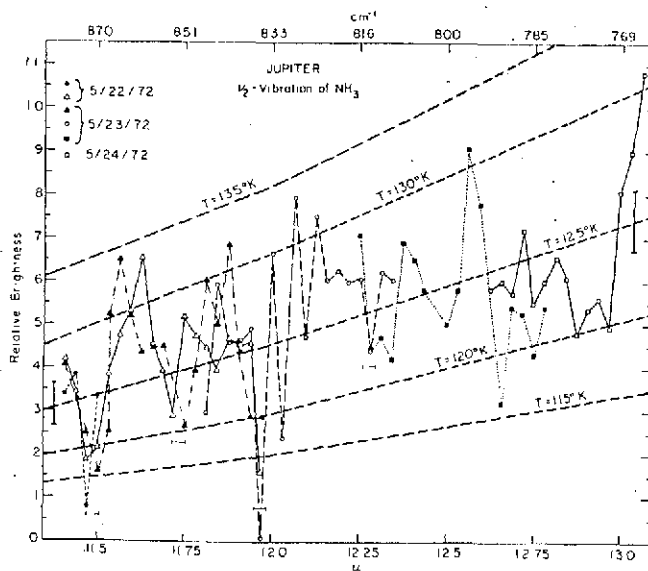


Figure 1. Jovian spectra. Different symbols represent different grating positions. The two sets of triangles represent spectra taken at different times.

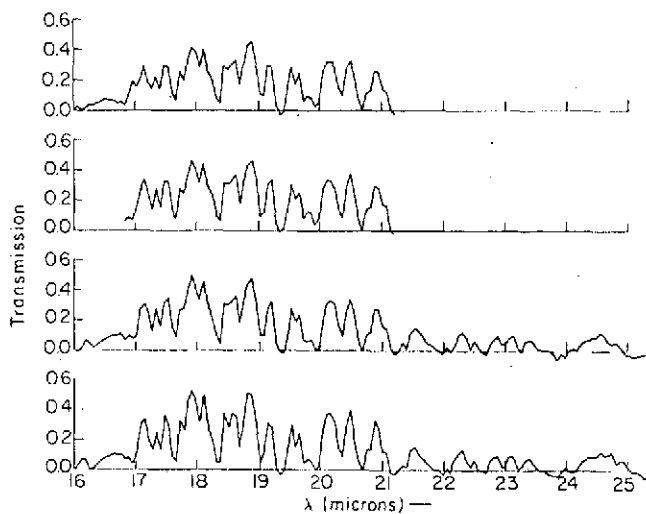


Figure 2. Atmospheric transmission profiles for four consecutive nights.

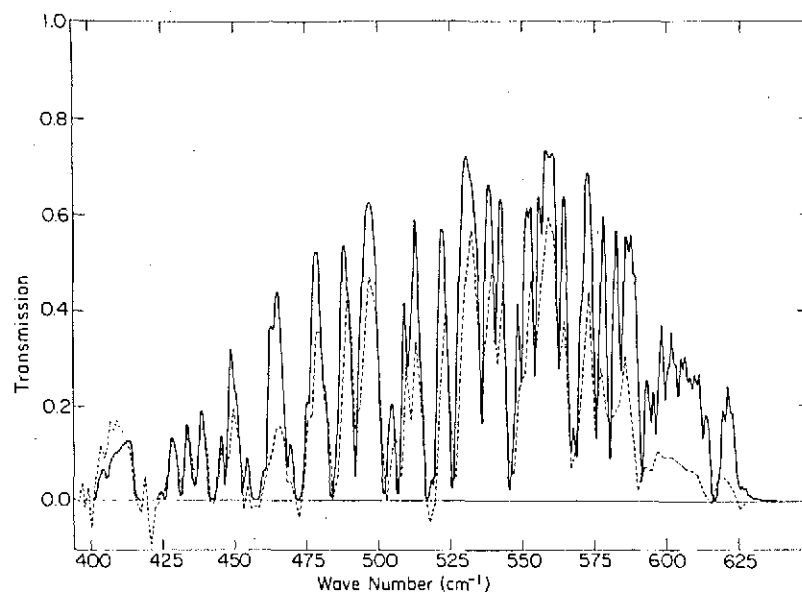


Figure 3. Comparison between experimental and theoretical transmission profiles. Smooth curve = theoretical results. Dashed lines = experimental data.

TABLE I.

DATE	PREC. H ₂ O (mm) ²	AIR MASS	LUNAR TEMP. (°K)
5/21/72	1.98	2.7	380
5/22/72	2.41	1.4	368
5/23/72	2.43	1.9	350
5/24/72	2.14	1.1	330
5/25/72	2.13	1.6	300