JUPITER'S MICROWAVE SPECTRUM: IMPLICATIONS FOR THE UPPER ATMOSPHERE

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Abstract. It is shown through the use of weighting functions that Jupiter's brightness temperature in the wavelength range 0.8–1.5 cm contains information on the thermal structure and abundance of ammonia in and above the tropopause in Jupiter's atmosphere. We present new data of Jupiter's brightness temperature in this wavelength range, and compare the results with theoretical spectra. The pressure in the Jovian atmosphere is estimated from these data to be 0.48 atm at 130K.

1. Introduction

It has long been recognized (Barrett, 1962) that microwave spectroscopy at short centimeter and millimeter wavelengths is a potentially effective means of studying the upper atmospheres of the major planets. Trace amounts of ammonia distributed in and above the clouds of the major planets are expected to produce line features in the planets thermal spectra near 1.25 cm wavelength due to the inversion splitting of the molecule's rotational energy states. The widths of these lines are dependent upon the pressure at the altitudes where they are formed. Within the ammonia clouds the pressure is thought to be sufficiently high ($\geqslant 1$ atm) that the individual lines are collision broadened into a single absorption feature a few GHz wide. In the atmospheric region above the clouds, where the pressure is a factor of ten or more less than the cloud pressures, narrow ammonia lines may form a fine structure superimposed on the broad absorption feature. Depending upon the thermal structure of the atmosphere, these narrow lines might appear either in emission or in absorption. Unfortunately, attempts to detect microwave spectral lines in the major planet spectra have been largely unsuccessful because of limitations imposed by sensitivity and calibration accuracy.

The most accurate data published to date are the broad band measurements of the thermal spectrum of Jupiter in the frequency range 20.5 GHz to 35.5 GHz by Wrixon *et al.* (1971). These measurements suggest the existence of the broad absorption feature discussed above, but the measurement uncertainties are too large to allow a quantitative interpretation. In this paper we report new observational data for Jupiter in the 20 GHz to 24 GHz band which 1) accurately define the slope of the low frequency ammonia absorption-line wing, and 2) set upper limits to the peak amplitude intensity of narrow (~ 50 MHz) emission or absorption lines relative to the continuum which might form in Jupiter's upper atmosphere. The pressure in the Jovian ammonia cloud is derived from the broad band data.

2. Theoretical Considerations

Previous theoretical investigations (Winter, 1964; Law and Staelin, 1968; Wrixon

Woszczyk and Iwaniszewska (eds.), Exploration of the Planetary System, 367–374.

et al., 1971; Gulkis and Poynter, 1972) have shown that a broad absorption feature centered near 1.25 cm should be present in Jupiter's microwave spectrum. We have made a series of model calculations to investigate how the spectral characteristics of such a feature depend upon specific atmospheric parameters. Our analysis shows that the slopes in the wings of the broad absorption depend primarily on the ammonia cloud pressure and only slightly on the ammonia mixing ratio and temperature below this cloud.

The models used in our analysis are in hydrostatic equilibrium throughout, with the troposphere in convective equilibrium, and with an isothermal stratosphere at 112 K. We assume that the major atmospheric constituent is H_2 and that trace amounts of ammonia (tropospheric mixing ratio $= 2 \times 10^{-4}$) provide the radio opacity. We

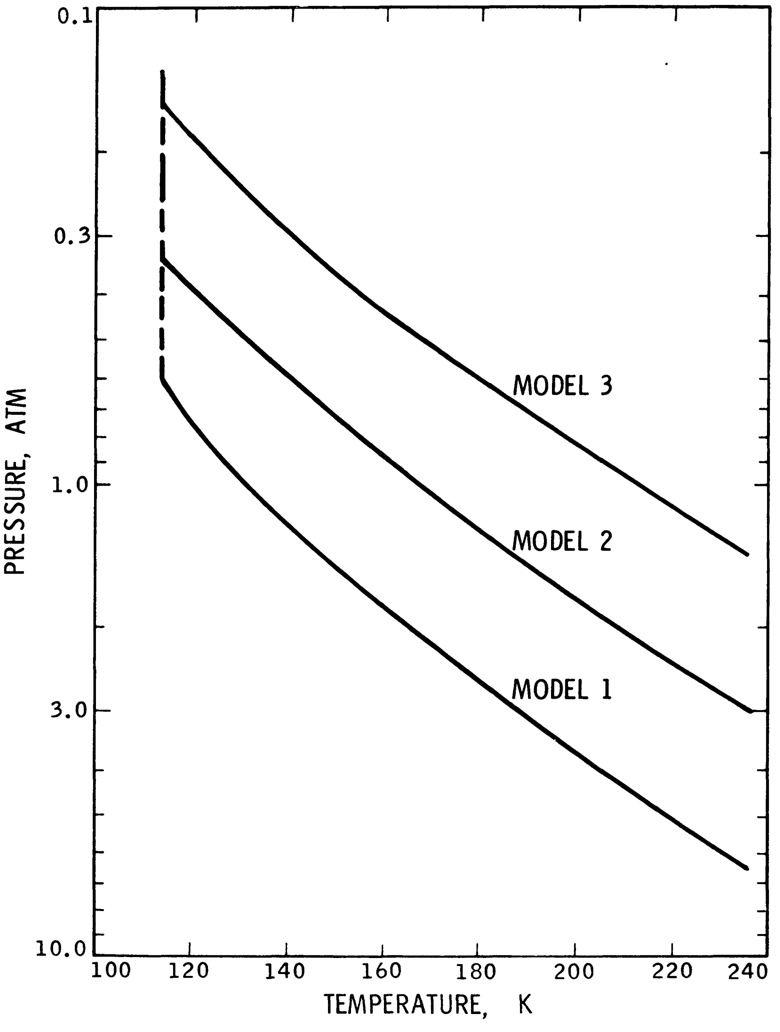

Fig. 1. Pressure-temperature models for the Jovian atmosphere.

consider the effects of including He as an additional major atmospheric constituent along with H_2 in the next section. The models are basically similar to those used by Gulkis and Poynter (1972) in their analysis of the longer wavelength portion of the microwave spectrum. In Figure 1 we show the basic model for three different cloud pressures typical of those found in the literature.

In order to define the slopes in the wings of the broad absorption line we solved the equation of transfer for a plane parallel atmosphere using the ammonia absorption coefficients computed by one of us (RLP). Scattering due to aerosols was assumed to be negligible for the wavelengths under consideration. We determined the frequency range most sensitive to the cloud pressure by computing the weighting functions for

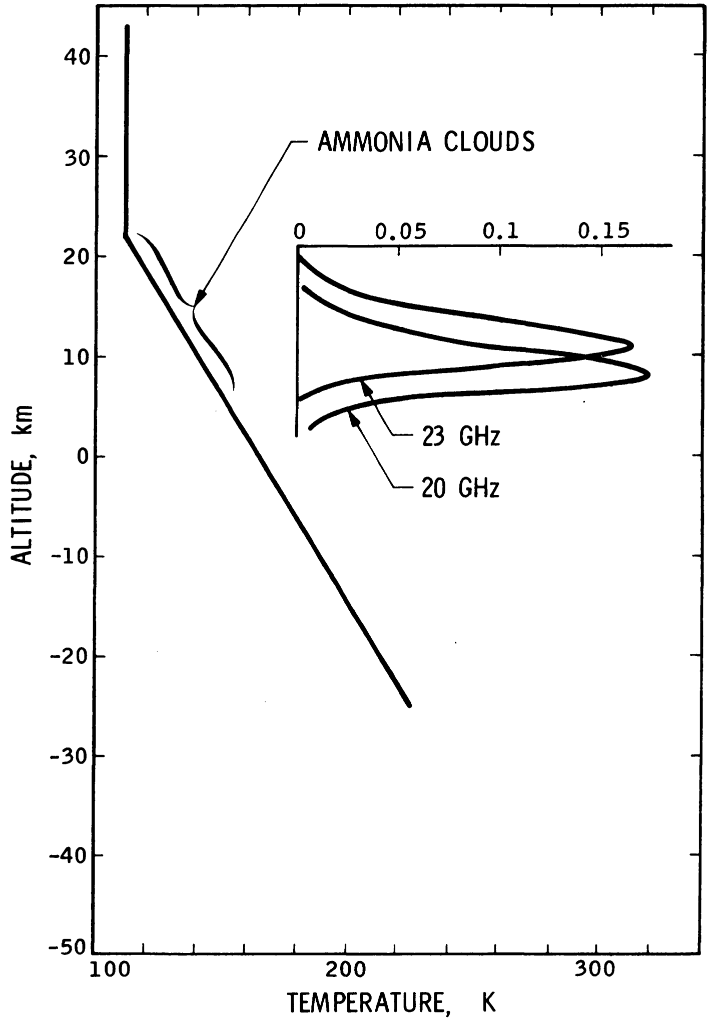

Fig. 2. Figure gives temperature-altitude profile for a model Jovian atmosphere. Insert shows the temperature weighting functions expressed in units of km^{-1} for two closely spaced frequencies.

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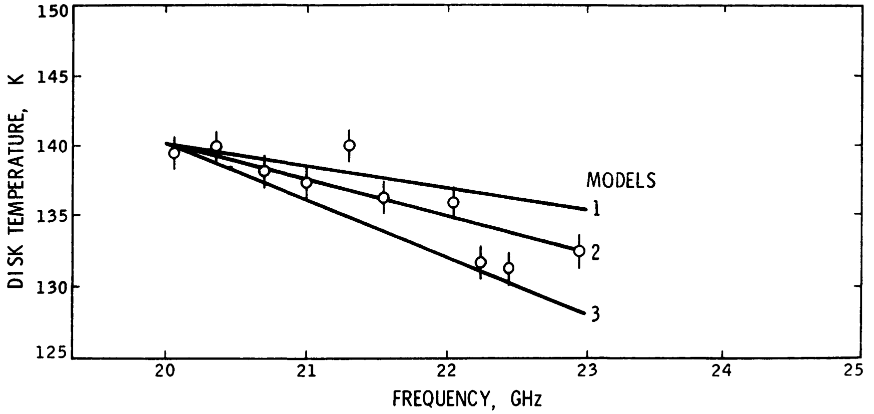

Fig. 3. Solid lines give theoretical spectral slopes for Models 1, 2, and 3. Experimental data are shown with one sigma uncertainties indicated.

a representative set of frequencies. The weighting function is a measure of the contribution which the kinetic temperature makes to the brightness temperature from each altitude increment. Weighting functions for two frequencies which are near the ammonia band center are shown in Figure 2. The weighting functions for these frequencies have an altitude resolution of less than 10 km and are primarily confined to the cloud forming region. Qualitatively, increasing the pressure in the clouds causes the weighting functions to converge toward a common altitude and tends to flatten the microwave spectrum. In contrast, decreasing the pressure causes the weighting functions to diverge and tends to increase the spectral slopes. The spectral slopes predicted by Models 1, 2, and 3 are shown in Figure 3. Their relationship with the observations is discussed in the next section.

3. Broad-Band Observations

In the spring of 1970 and again in 1971 we observed Jupiter to confirm the existence of the broad ammonia absorption feature and to search for discrete spectral features at the frequencies of the more intense ammonia lines. We used the 9-m antenna at the Venus Station of the NASA Deep Space Instrumentation Facility, Goldstone, California. The receiver consisted of two broad-band (20–24 GHz) traveling-wave-tube amplifiers followed by a parallel set of 13 tuned r.f. filters and separate detectors. The filter bandwidths ranged from 20 MHz to 180 MHz. The relative precision of the spectral measurements was enhanced with this system because all thirteen frequencies were simultaneously observed. The radio source Cassiopeia A was observed each night for calibration purposes.

The principal results of these observations are: (a) the Jovian brightness temperature decreases approximately 7 K between 20 GHz and 23 GHz and either remains constant or increases slightly between 23 GHz and 24 GHz; (b) the disk temperature at 23.5 GHz is 132 ± 10 K (total standard error). This temperature is in good agreement with the absolute brightness temperature measurements of Wrixon *et al.* (1971), and with theoretical calculations based on model atmospheres in which the upper atmosphere is saturated with ammonia.

The results most relevant to the determination of the pressure in the ammonia cloud are the observed temperatures between 20 GHz and 23 GHz. These data are shown in Figure 3 superimposed upon the predicted spectra for the three theoretical models which are normalized to a temperature of 140 K at 20 GHz. We note that Models 1 and 3 predict slopes that are too shallow and too steep, respectively, compared with the data.

Based on a Chi-square analysis for which we assumed nine degrees of freedom (number of data points minus one for the slope), we conclude that Models 1 and 3 can be excluded at the 95% confidence level while Model 2 provides an adequate fit to the data. Since the collision cross section of helium is about a factor of three smaller than that of hydrogen, the total pressure implied by the models depends on the helium-to-hydrogen number mixing ratio. For a pure hydrogen atmosphere, our best estimate of the pressure at a temperature of 130 K is 0.48 atm with a 95% probability that it lies between 0.24 atm and 0.97 atm. Our estimate of the pressure increases by about ten percent if the helium-to-hydrogen number mixing ratio is increased from zero to 0.2.

4. Narrow Band Observations

In July 1972 and May 1973 we attempted to detect narrow band ammonia lines in the Jovian spectrum near 1.25 cm. The observations were made with the 40-m radio telescope at the Owens Valley Radio Observatory operated by the California Institute of Technology. The receiver was a double sideband balanced mixer with a tunable local oscillator. The system temperature was about 2000 K. The intermediate frequency amplifier was followed by a power divider at the input of a six-channel filter bank with filter widths of about 40 MHz. The outputs from the six channels were separately detected and digitally recorded. In addition to the six narrow band channels, the signal from the full IF passband between 20 MHz and 300 MHz was simultaneously detected and recorded. Each individual filter response was normalized to the response of the full IF bandwidth to minimize the adverse effects of antenna tracking errors and differential extinction in the Earth's atmosphere. Spectral features introduced by the receiver and the antenna feed system were removed by dividing all the Jupiter results by measurements of the Moon and other radio sources which were observed for calibration purposes. We obtained confidence that the system was performing properly by observing the water line in the Orion Nebula.

The 1972 observations were made at three different local oscillator frequencies. One of these was repeated and two new frequencies were observed in 1973. The five frequencies were 22.395 GHz, 22.687 GHz, 23.532 GHz, 23.785 GHz, and 24.004 GHz. The observed spectra for each of the five frequencies were compared with the corresponding theoretical spectra which were computed by convolving the model brightness temperatures with the filter response function. The process was repeated for a number

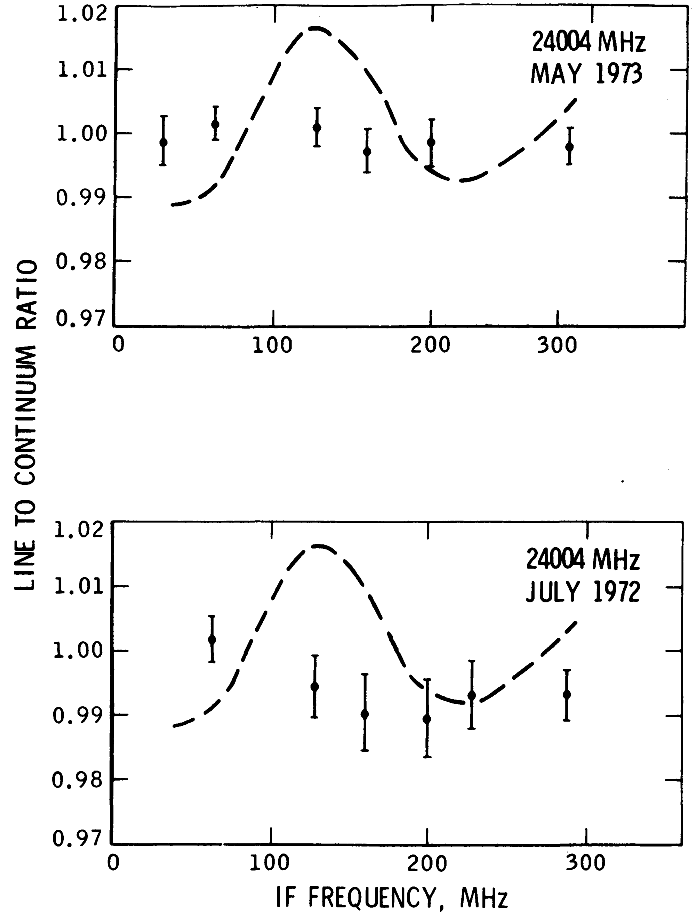

Fig. 4. Narrow band observational data are shown with one sigma uncertainties indicated. Local oscillator frequency setting used for these data was 24004 MHz.

of models in which the narrow line features varied from ~4% emission to ~4% absorption relative to the broad absorption continuum. A preliminary analysis of our results for the various Chi-square values allows us to conclude that any absorption or emission spectral features that may exist at these five frequencies have amplitudes of less than 2% relative to the continuum. This result is made with 90% confidence factor for line widths between 20 MHz and 100 MHz.

Figure 4 shows our measurements for one representative frequency, 24004 MHz, along with their one-sigma error bars. These spectra show no evidence of any strong narrow band emission or absorption feature. For comparison, the dashed curve represents a theoretical spectrum for a model in which 4% emission lines are present.

5. Concluding Remarks

The broad band data presented in Figure 3 clearly establishes the existence of a slope

[~2.5 K GHz^{-1}] in Jupiter's microwave spectrum between 20 GHz and 23 GHz. We believe that absorption in the low frequency wing of the pressure-broadened ammonia inversion band is the most plausible explanation of the observed slope. Based on this interpretation the data imply the existence of a saturated ammonia cloud with an equivalent H_2 pressure of 0.48 atm at 130 K.

The absence of narrow ammonia lines in Jupiter's spectrum can most easily be explained by limiting the high altitude ammonia abundance. If ammonia is distributed in the stratosphere according to hydrostatic equilibrium with the reference value of the partial pressure of ammonia chosen equal to its vapor pressure at the minimum temperature reached at the tropopause, then our observations suggest that the minimum temperature is less than 120 K. This result is consistent with the recent measurements by Gillett *et al.* (1969) and Gillett and Westphal (1973) which suggest the presence of a thermal inversion in the stratosphere. However, our results do conflict with a preliminary summary of observations by Wrixon (1969) who also observed the most intense ammonia lines. He reported the detection of narrow emission lines and estimated that they would be explained if 0.06 cm-atm of ammonia were present in a thin layer above the clouds at a temperature and pressure of 145–155 K and 6.5 mb. Using these atmospheric parameters we computed the theoretical spectral response for our filters. The response for one frequency is compared with our observed spectrum in Figure 4. We see no evidence that would confirm the lines reported by Wrixon (1969) in either the 1972 or the 1973 data.

Acknowledgements

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DISCUSSION

Owen: Please explain again the determination of the minimum temperature.

Gulkis: If ammonia is distributed in the stratosphere according to hydrostatic equilibrium, with the reference value of the partial pressure at the minimum temperature reached at the tropopause, then the *maximum* value the temperature can reach is 120 K. This limits the high altitude abundance to a sufficiently low value that any narrow lines which might form would be below our detection limit.

Gautier: What is the influence of the assumed thermal model on the level of the peak of the computed weight-function (remembering that the partial pressure of ammonia is, in the zone of saturation, only a function of the temperature)?

Gulkis: We have not computed the brightness temperatures for models in which the lapse rate departs from an adiabatic rate; however I expect that a sub-adiabatic rate will cause the weighting functions to shift to higher altitudes. Consequently the brightness temperature should decrease. It will be interesting to examine how the differential brightness temperature changes as a function of lapse rate.