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Jupiter: Its Infrared Spectrum from 16 to 40 Microns

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ABSTRACT

Spectral measurements of the thermal radiation from Jupiter in the 16-40µm band are analyzed under the assumption that pressure broadened H_2 transitions are responsible for the bulk of the infrared opacity over most of this spectral interval. Both the vertical pressure-temperature profile and the hydrogen mixing ratio are determined. The derived value of the molecular hydrogen mixing ratio, 0.89 ± 0.11, is consistent with the solar value, 0.86.

The abundance of hydrogen and helium in the Jovian atmosphere has a direct influence on a number of astronomical problems. Jupiter's low atmospheric temperature and great mass prevents even the lightest atoms from escaping from the top of the atmosphere. Therefore, Jupiter as a whole is a sample of the elemental abundance at the time of its formation. Modern theories of explosive neucleosynthesis show that the majority of the helium presently in the universe was formed during the Big Bang(1). Further, it has been shown that the relative abundance of hydrogen and helium depends strongly on the temperature and density during the early stages of the evolution. To the extent that the Jovian atmosphere is representative of the planet as a whole, a measure of the hydrogen mixing ratio $\alpha_{H_2} = N(H_2)/N(H_2)+N(He)$ where N(x) is the number density of x) in the atmosphere is useful for the determination of the conditions during the early stages of the Big Bang. There are, however, several effects which may systematically distort the atmospheric value of α_{H_2}.

Opik has suggested a model for the formation of Jupiter in which first "hydrogen snow" collects to form a core followed by the capture of a helium rich atmosphere(2). Salpeter has suggested that there may be internal differentiation with the helium sinking toward the center of the planet resulting in a hydrogen rich atmosphere(3).

Observations

Jupiter was observed on the nights of 1973 November 14 and 16 and 1974 January 21 using a 31 cm telescope mounted on the NASA Ames Lear Jet. The aircraft was flown to an altitude of 14 km (45,000 ft.). At this altitude about 3 to 10 precipitable microns of water per airmass remain above the observer. The telescope viewed the source at elevation angles between 14 and 28° (4.1 to 2.1 airmass). The spectral scans were made using two different liquid Helium cooled grating spectrometers(4). These instruments employ a 12.5 cm focal length Ebert-Fastie spectrometer with two detectors in the focal plane. The No. 1 instrument has a Ge:Cu photoconductor to scan the 16-28μm band while a Ge:Ga photoconductor covers 20-40μm. The resolution of the two channels is 0.5μ and 1.0μ respectively. The No. 2 instrument has two Ge:Cu photoconductors and covers the range 16-28μm with a resolution of 0.5μm. The instruments operate at f/6.5 and have a 2.7 mm entrance aperture corresponding to 4.7 minutes of arc. The chopping frequency was 48 Hz.

The instrumental response was determined by normalizing spectra of the Moon and Mars as if they were black body radiators at 350°K and 240°K respectively. The instrumental profile determined in this way was used to normalize the Jupiter data. The resulting spectrum is shown in Fig. 1. The figure shows the presence of three absorption features at 18, 23.5 and 28μm. The first and last are the J = 1 and J = 0 rotational transitions of molecular hydrogen. The 23.5μm feature is unidentified but may be due to sulphur, silicate dust or complex hydrocarbons in the atmosphere.(5) All of these material have strong absorption features in this wavelength region. A complete discussion of these possibilities will be given by Pollack et al.(6)

Data Analysis

The observed spectrum of Jupiter contains information about both a portion of its vertical temperature structure and its helium to hydrogen ratio. Before describing our numerical method for deriving this information, we describe the basis of our ability to do so. The brightness temperature found at a given wavelength is approximately equal to the value of the physical temperature in the Jovian atmosphere at optical depth unity. As the wavelength is varied, the altitude where the optical depth is unity also varies. Thus, spectral observations over a range of wavelengths provide information on the temperature conditions over a corresponding range of altitudes in the atmosphere. For the spectral band measured, molecular hydrogen is the principal source of opacity. The Jovian atmosphere is probed from about the 0.15 atmosphere level to the 0.6 atmosphere level, a region which includes a temperature minimum and the top of the convection zone.

In performing the analysis described below we excluded data close to the 23μm feature. In addition to opacity due to the rotational and translational transitions of hydrogen we allowed for opacity due to ammonia, which is important only at the long wavelength edge of our data. We performed calculations both without and with an optically thick ammonia cloud present in the zone regions of Jupiter, located at the ammonia saturation level of the atmosphere.

In accord with radio temperature measurements we assumed that the temperature gradient equalled the adiabatic value at pressures greater than the bottom altitude boundary of the region we sense(7). Our derived temperature profiles are consistent with this assumption. Above our top altitude boundary we made use of the temperature gradients derived by Orton from an analysis of measurements in the region of the 7.7μm methane band.[8]

Our ability to gain information about the helium to hydrogen ratio follows from the dependence of the hydrogen pressure induced transitions on this ratio. This dependence is illustrated in Figure

1, which shows the values of the absorption coefficient of hydrogen when the rotational transitions occur in the presence of a nearby hydrogen molecule, (H_2-H_2) and in the presence of a nearby helium atom (H_2-He). We see from Figure 1 that the absorption coefficient shows a different spectral variation for the (H_2-He) case than for the (H_2-H_2) case.

The numerical method used to obtain the desired information from the observed spectrum of Jupiter begins with an assumed trial value of the hydrogen mixing ratio, α_{H_2}. For this choice of mixing ratio, the observed spectrum is inverted to determine the pressure-temperature structure by means of a statistical iteration technique developed by Smith and applied to planetary atmospheres by Ohring(9,10). This method involves starting with a trial temperature profile, computing a predicted spectrum with this profile, and correcting the profile on the basis of the difference between the observed and calculated flux values, the flux residuals. The improved guess is used to repeat this process and, after a small number of iterations, the r.m.s. of the flux residuals approaches an asymptotic value. This procedure is repeated for other trial values of α_{H_2}. An estimate of the helium ratio was obtained from the locations of the minimum in the value of the flux residual as a function of mixing ratio.

Results

Figure 2 shows the vertical temperature structure of Jupiter determined from our spectrum for hydrogen mixing ratios of 0.8, 0.9 and 1.0. These results refer to models containing no ammonia cloud opacity. However, very similar curves were obtained for runs with optically thick clouds. Our results have been smoothly joined with the temperature gradients found above and below our region of sensing. Figure 2 also indicates the location of the regions probed in our measurement, at radio wavelengths, and within the 7.7μm methane band. The temperature values found from these various determinations are quite consistent near their boundaries. The temperature gradient becomes adiabatic at the higher pressure domain of our sensing region, which is consistent with the temperature lapse rate implied by the radio results. We find that the lapse rate first reaches the adiabatic value and therefore that the convection zone begins at approximately the 0.4 atmosphere pressure level. This result is in good agreement with the theoretical predictions of Pollack and Ohring(11), which were based on a radiative equilibrium model. Our measurements also suggest the presence of a temperature minimum and the start of an inversion layer at the lower pressure levels of our region. This aspect of the temperature profile is suggested by the small displacement of the observed minimum in our brightness temperature spectrum from the center of the J = 1 hydrogen rotational transitions. These results are in accord with Orton's analysis of measurements made in a spectral region containing the 7.7μm fundamental of methane. Also the value of our temperature minimum (115°K) is in good agreement with Orton's value of about 118°K.

The temperature profiles shown in Figure 2 are in conflict with the structure found from a preliminary analysis of the Pioneer 10 S band occultation experiment(12). The latter results indicate a much warmer atmosphere than our results at pressures above several millibars. Our infrared observations could be reconciled with the S band data if we postulate the presence of an optically thick cloud near the 1 millibar pressure region. However, in this case the pressure induced opacity of hydrogen would be negligible and we would not expect to detect the J = 0 and J = 1 rotational transitions in our spectrum. The presence of these features in our spectrum suggests that further study of the S band occultation results is needed. These conclusions are also supported by the consistency of our temperature profile with values obtained at shorter infrared wavelengths and in the radio domain, as discussed above.

For models containing no ammonia cloud opacity in the zones of Jupiter, we find that the hydrogen mixing ratio is 0.85 ± 0.07, while we obtain a value of $1.0^{+0}_{-0.04}$ for the cases involving an optically thick ammonia cloud. These error bars reflect only the formal random errors of our results. We note that the cloud free models had a smaller value for the minimum fractional flux residual than the latter set (0.039 vs 0.043). Combining the above two estimates, we conclude that the hydrogen mixing ratio equals 0.89 ± 0.11. This range of values encompasses the solar value of 0.86.

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FIGURE CAPTIONS

Figure 1. a. The brightness temperature of Jupiter is shown for wavelengths from 16 to 40µm.

b. The pressure induced absorption coefficients for H_2-He collisions are shown. The curves shown represent the sum of both translational and rotational transitions.

Figure 2. A plot of the derived pressure temperature profile for the Jovian atmosphere is shown. The pressure level most directly measured by various observational techniques is shown.

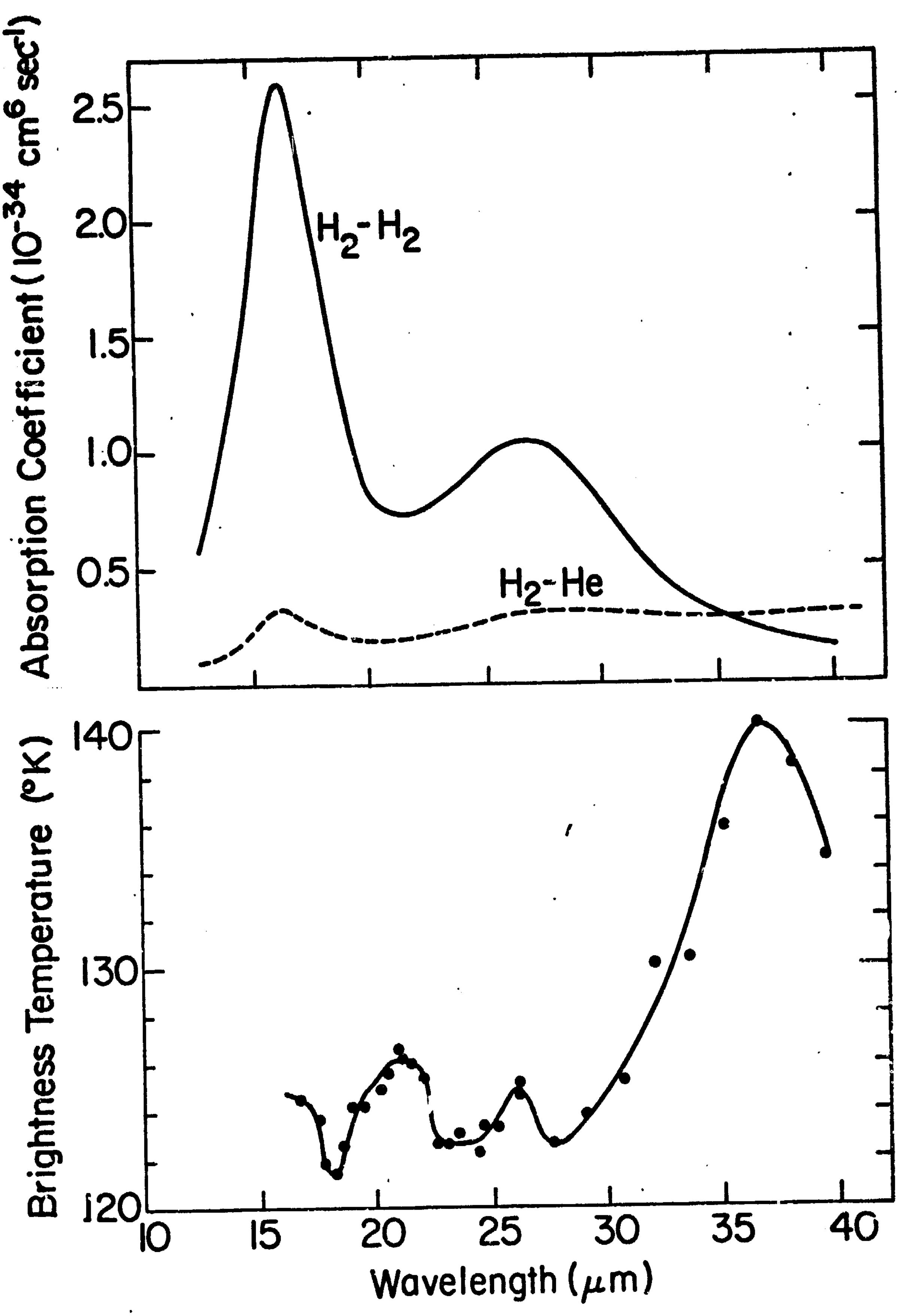

Figure 1

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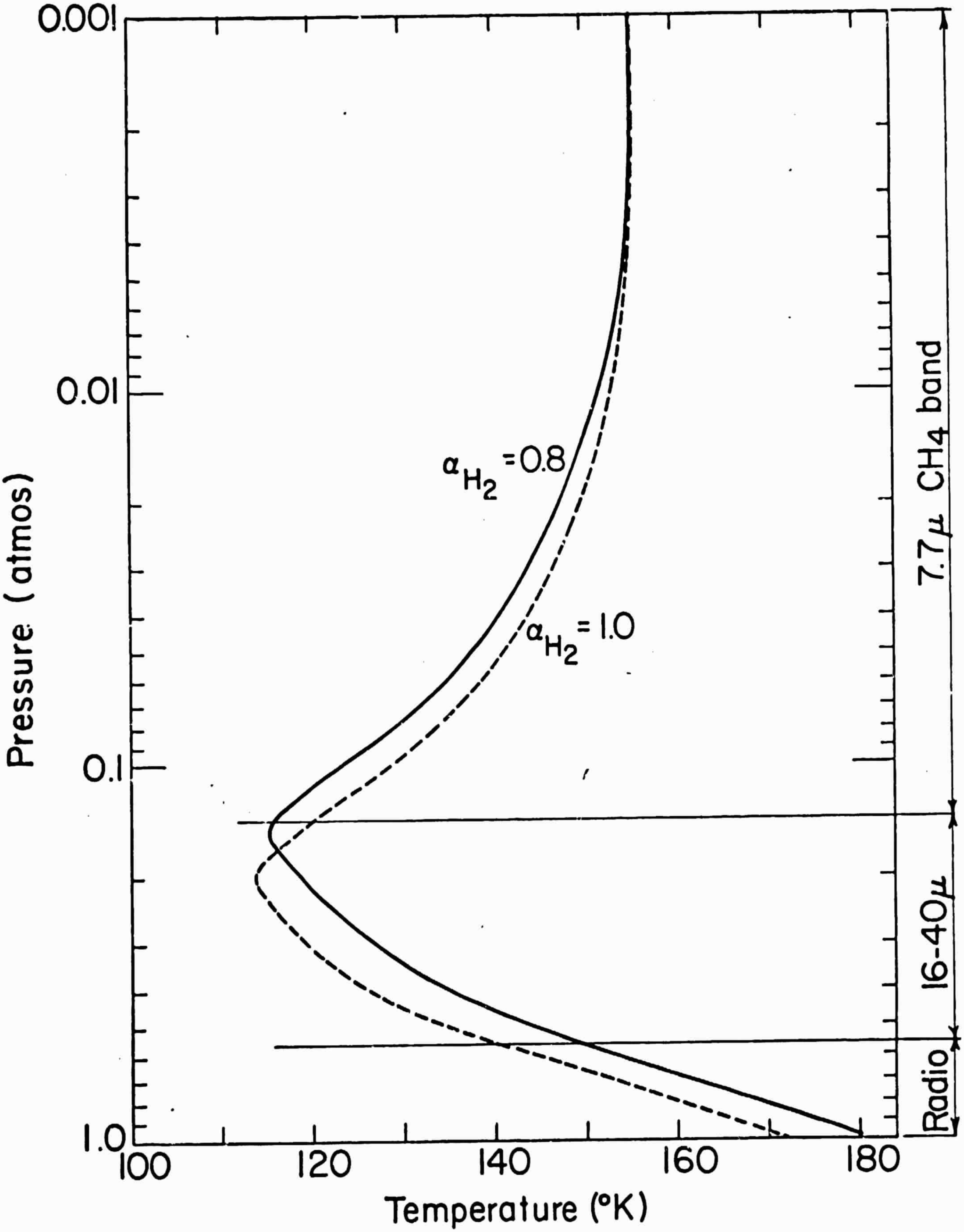
0.001
0.01
0.1
1.0
Pressure (atmos)
100
120
140
160
180
Temperature (°K)
$\alpha_{H_2}=0.8$
$\alpha_{H_2}=1.0$
7.7μ CH4 band
16-40μ
Radio

Figure 2