ICARUS 39, 28–45 (1979)

Atmospheric Thermal Structures of the Giant Planets

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Received June 15, 1978; revised March 2, 1979

Thermal models of planetary atmospheres can be calculated from assumptions of the energy budget of the atmosphere and from the knowledge of the effective temperature of the studied planet. On the other hand, the retrieval of the thermal atmospheric profiles from infrared measurements by means of the numerical inversion of the radiative transfer equation presents the advantages of not requiring such assumptions. The extent of the atmospheric range which can then be sounded is examined and the vertical resolution of the inferred profiles is discussed. Comparisons of thermal models and of retrieved thermal profiles are made for the four giant planets. The retrieved profiles lead to brightness temperature spectra which fit all the available infrared measurements fairly well for Jupiter and Saturn but only part of them for Uranus and Neptune. The values of the planetary effective temperatures calculated from the retrieved profiles show that Jupiter, Saturn, and Neptune have strong internal heating sources while Uranus probably has a very small or null one.

1. INTRODUCTION

The Two Approaches for Determining the Thermal Structure of Planetary Atmospheres

There are two approaches to determining the thermal structures of the thick planetary atmospheres. The first, which was the first one to be used, consists of computing thermal atmospheric models from convenient assumptions of the energy budget of the atmosphere and from the knowledge of the effective temperature of the studied planet.

The procedure is the following: given the values of the incident solar radiation and of the energy flux outgoing from the atmosphere, the downward and upward radiative fluxes are calculated at each level from the accurate knowledge of the abundances of the atmospheric components and of their absorption coefficients. Assuming the conservation of the net flux of energy at each level, the vertical distribution of the source function in the medium can be determined. With the additional hypothesis of the existence of local thermodynamic equilibrium in the medium, the local temperature is obtained since the source function becomes the Planck function. In the deep layers of the atmosphere, the energy is mainly transferred by convection. The well-known Schwarzchild criterion leads to the assumption that the actual temperature gradient is equal to the

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adiabatic lapse rate when the radiative gradient becomes superior to the latter.

The technique of computing atmospheric models is powerful and allows us to understand the physical behavior of the studied atmosphere. However, it is not very flexible as it requires us to know accurately all the sources and sinks of energy, and in the absence of approximations, it consumes a large amount of computer time. The only constraint is the effective temperature so that the comparison with the observed spectrum can only be made a posteriori.

The most recent application of this technique in the nongray case was made by Wallace *et al.* (1974) and Wallace (1975b) for the four giant planets.

Analytical approximations for the opacities allow various authors to simplify the calculation of models and an analytical formulation of the thermal profile was derived by Cess and Khetan (1973).

These approximations can produce temperature profiles in good agreement with those deduced from more detailed calculations, and, as detailed in Sec. 3, they can give a good representation of the actual thermal profile. However, the physical implications of such approximations are sometimes uncertain.

A second approach consists in retrieving the atmospheric thermal structure by inversion of the integral equation of radiative transfer, from properly chosen infrared spectral measurements (or from center-to-limb radiance measurements). This technique is based on the fact that, at wavelengths where the reflected solar radiation can be neglected (this is verified in the far-infrared range), the radiative flux from a thick planetary atmosphere at a given frequency is simply related, in a first approximation, to the temperature of an atmospheric layer the altitude of which depends on the absorption coefficient of the gas responsible for the emission. Since, usually, the absorption coefficient varies with frequency, the altitude of the sounded layer also varies. From a set of properly chosen spectral measurements of the outgoing intensity, it is then possible to retrieve the thermal profile in a part of the vertical extent of the studied atmosphere.

Since the opacity also varies as a function of the cosine of the local angle of emission, the same procedure can be applied to the inversion of center-to-limb radiances.

The so-obtained profiles lead to brightness temperature spectra which fit all the experimental data—except if they are in conflict with each other—and also allow us to calculate the effective temperature of the studied planet.

In fact, the two approaches are complementary since the inversion technique presents the advantages—beyond its simplicity—of not requiring restrictive assumptions on the energy budget of the atmosphere while only the modeling approach allows us to understand the physical processes which rule the thermal behavior of the sounded atmosphere.

In this perspective, the purpose of this paper is to compare the available atmospheric thermal models of the four giant planets to the profiles retrieved by means of inversion techniques and to examine what consequences can be derived relative to the physics of their atmospheres. However, it is first necessary to clearly understand the limitations of the inversion method.

2. LIMITATIONS OF THE INVERSION TECHNIQUE

To be used, the inversion technique requires that the emitting constituent is uniformly mixed in the sounded part of the atmosphere, that its mixing ratio is known, and that the medium is in local thermodynamic equilibrium. Moreover, limitations come from the spectral behavior of the absorbers and from the mathematical properties of the integral equation of the radiative transfer.

In the case of the giant planets, hydrogen and helium—and methane for Jupiter and Saturn—have mixing ratios constant with height up to very high atmospheric levels. The pressure-induced absorption due to collisions between hydrogen molecules and between hydrogen and helium is responsible for the spectrum of the giant planets in a large part of the far-infrared range. The curves of Fig. 1 indicate the atmospheric pressure levels of Jupiter, Saturn, and Neptune, which are sounded when measurements are made at a given frequency located in the H_2–He absorption range. The curve for Uranus is very similar to the one for Neptune and has been omitted for clarity. For Jupiter, the presence of ammonia absorption bands limits the usable spectral interval to the range 12 to 37 μm (270–800 cm^{-1}), while for the three other giant planets, the H_2–He opacity is predominant up to millimetric wavelengths (except at some discrete wavelengths in the case of Saturn (Encrenaz and Combes, 1977)). The thermal profile of the lower atmosphere then can be retrieved from measurements in the H_2–He range. On the other hand, the very strong ν_4 band of CH_4, centered at 7.7 μm allows us to get information on the upper atmosphere. However, this information is somewhat ambiguous for reasons detailed below.

The key point is that the experimental noise limits the amount of information which can be retrieved by inverting the radiative transfer equation. To avoid spurious oscillations in the solution due to the amplification of the high-frequency components of the Fourier spectrum of the noise by the inversion process, a procedure of filtering must be introduced in any stable inversion method (Gautier and Revah, 1975). As a consequence, the vertical resolution of the inferred profile is limited so that the fine thermal structure cannot be retrieved.

The value of the maximal vertical resolution which can be obtained depends on the following factors:

—First, the use of a limited spectral resolution to measure the planetary outgoing flux can deteriorate the information. The measurement of the H_2–He spectrum requires a relatively low spectral resolution (5–10 cm^{-1}) while an optimal measurement of the CH_4 spectrum would require an extremely high resolution eventually equal to the Doppler width of the emission lines (i.e., about 2×10^{-3} wavenumber).

—Second, at a given spectral resolution, the maximum vertical resolution of the retrieved profile depends upon the signal-to-noise ratio of the measurements. The higher the noise level, the more severe the filtering of the Fourier spectrum of the signal, and thus the smoother the retrieved profile.

—Finally, for given spectral resolution and signal-to-noise ratio, the vertical resolution depends on the variation of the opacity of the absorbing gas upon the pressure. A fast variation leads to a high vertical resolution while a slow variation leads to a poor resolution. Therefore, the H_2–He collision-induced absorption which is proportional to the square of the pressure allows us to obtain a vertical resolution significantly higher than the CH_4 absorption which varies as a power of the pressure less than unity. (An intuitive evidence of such behavior can be inferred from the examination of the corresponding weighting functions (cf. for instance, Orton (1977), Fig. 3).)

In the case of Jupiter, Gautier and Revah (1975) from a Fourier analysis and Orton (1977) and Hanel *et al.* (1977) from a Backus–Gilbert analysis adapted to the radiative transfer equation by Conrath (1972) have calculated the maximum vertical resolution which can be obtained from various spectral measurements of the intensity outgoing from the planet. The three analyses converge towards the same qualitative results. For the part of the profile which is retrieved by use of the H_2–He opacity, the vertical structure can be as good as 0.5 scale height, but it is significantly less for the stratospheric profile which is retrieved by use of the weakly pressure-dependent methane opacity.

Therefore, only a crude structure of the stratosphere thermal profile can be determined from the presently available measurements. The same analysis is qualitatively valid for the other giant planets, but the stratosphere thermal structure of Uranus cannot be determined since at the present time no emission in the ν_4 band of methane has been observed.

At this step, the concept of a limited vertical resolution of the retrieved profile must be well understood. From any "good" inversion method using a proper filtering procedure, the zero-frequency and the low-frequency Fourier components of the actual thermal profile are retrieved (within the calibration errors of the measurements). The retrieved profile is only a smoothing of the actual profile. It is the simplest thermal structure which leads to brightness temperature spectra and an effective temperature value which fit (usually in the sense of the least squares) experimental measurements. Should the vertical resolution be improved from correct additional information (as from occultation measurements, modeling, ...), the corresponding thermal profile would lead to the same fit of the experimental infrared measurements since the so-added fine structure contributes to high-frequency Fourier components of the thermal flux which are masked by the experimental noise. The importance of these remarks will appear in the following section.

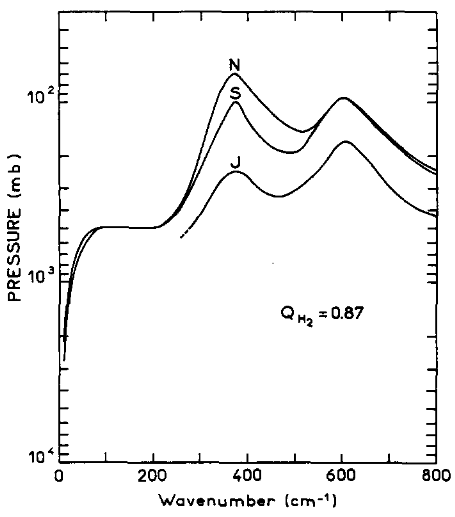

FIG. 1. Variation versus wavenumber of the atmospheric pressure level which is sounded when a spectral measurement of the full-disk intensity is made at a given wavenumber. J refers to Jupiter, S to Saturn, and N to Neptune. The atmospheres are assumed to be composed of 87% hydrogen and of 13% helium.

3. ATMOSPHERIC THERMAL PROFILES

A. Jupiter

The recent airborne spectral measurements by Aumann and Orton (1976) and by Erickson *et al.* (1978) in the far-infrared range and by Russell and Soifer (1977) in the 8-μm range have significantly improved the determination of the Jovian thermal structure. Figure 2 shows three thermal profiles retrieved from the same infrared data, assuming the same hydrogen-to-helium ratio and close methane-to-hydrogen ratios. Orton (1977) used the weighted inversion method of Chahine (1972) while Gautier *et al.* (1977a) have introduced a filtering process in the original algorithm of Chahine (1968, 1970). These two methods can differ in computation time but should give very similar results if the same opacities are used. Concerning the hydrogen–helium opacity, some uncertainty is unavoidable at the present time since the best available laboratory measurements of the H_2–H_2 and H_2–He absorption coefficients (Birnbaum, 1978) are given with an accuracy of only $\pm 5\%$. However, the problem of determining the variation

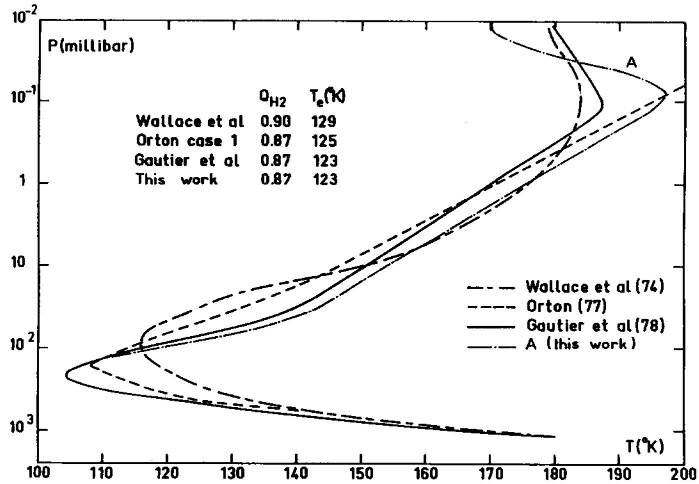

FIG. 2. Retrieved profiles of Jupiter from Orton (1977), Gautier *et al.* (1979), compared to the retrieved profile A (cf. text) and to model C of Wallace *et al.* (1974).

of the H_2–H_2 absorption as a function of frequency and temperature seems to have been solved from the lineshape theory of Birnbaum and Cohen (1976). Greater sources of uncertainty on the retrieval of the tropospheric thermal structure lies in our ignorance of the radiative properties of the Jovian clouds and in the uncertainty on the H_2/He mixing ratio.

There is a strong presumption that the observed depression of the spectrum of Jupiter in the 1050- to 1200-cm^{-1} region (Ridgway *et al.*, 1976) is due to NH_3 crystals which exhibit a strong and broad absorption band centered at about 1050 cm^{-1} (Taylor, 1973). Orton (1975, 1977) has been able to fit the low-resolution spectrum of Jupiter between 1050 and 1220 cm^{-1} by introducing a partially transparent haze above an optically thick cloud located at the level of 140° to 148°K. Such a structure could also introduce perturbations in the radiative transfer in the H_2–He absorption range and then modify the retrieval of the thermal structure. As a matter of fact, the large number of parameters required to describe the radiative transfer through aerosols does not allow us to infer the physical properties of the particles (size, distribution ...) from the 8- to 9.5-μm spectrum. Various kinds of perturbations are then possible. For large size particles—10 μm or more as claimed by Rossow (1978) from theoretical considerations on the precipitation time scales—a significant scattering should exist in the far-infrared range, modifying the simple LTE formulation of the radiative transfer equation. However, Orton and Terrile (1978) from observations of the Jovian clouds find that the precipitation time scales are much longer than Rossow's estimates and accordingly, the particles sizes should be smaller. For small-size particles—1 μm or less—the scattering should be negligible in the far-infrared region but a NH_3 solid absorption could be significant at some wavelengths (Taylor, 1973). Even in this case, a dense cloud can be opaque at all wavelengths, and then could perturb the infrared sounding of the deepest layers. However, the degree of obscurity of the field of view by clouds is completely unknown. Orton (1977) has compared the extreme case, where a cloud opaque to all wavelengths (with no scattering) is introduced at the 148°K level to the case completely clear of obscurity and has found a difference lower than 3.5°K between 0.6 and 0.4 bar and insignificant at higher levels.

The relative abundance q of H_2 is estimated, from both infrared and ultraviolet measurements, to be between 0.8 and 0.94 (Orton and Ingersoll, 1976: Gautier *et al.*, 1977a). The profiles corresponding to these extreme values are close in the upper troposphere but diverge at deeper levels since the adiabatic extrapolation depends on the hydrogen-to-helium ratio.

The extreme tropospheric profiles 5 and 6 retrieved by Gautier *et al.* (1979) from, respectively, the data of Erickson *et al.* (1978) for $q = 0.8$ and the data of Aumann and Orton (1976) for $q = 0.94$, differ by about 20°K at the 1-bar level and by 40°K at the 10-bar level. This evaluation of the uncertainty seems reasonably conservative concerning the thermal structure of the lower troposphere. The retrieved profiles, Case 1 of Orton (1977) and of Gautier *et al.* (1979), which correspond to the same mean value of q are very close to each other (Fig. 2) and both lead to a reasonably good fit of the presently available infrared measurements (Fig. 3).

In regard to the stratosphere, the situation is much less satisfactory because of the low spectral resolution and the inaccuracy of the experimental data. Both measurements of Gillett (1973) and of Russell and Soifer (1977) are made with a resolution of only about 20 cm^{-1}. Moreover, it is not possible to fit the whole set of the Jovian measurements in the ν_4 band spectrum from any thermal profile, which could indicate the presence of another absorber (probably NH_3 haze for $\nu < 1240$ cm^{-1}) or a bad calibration due to the very weak telluric transmission for $\nu < 1300$ cm^{-1} (as confirmed by the first results of the Voyager mission). Therefore, only the range of 1240 to 1280 cm^{-1} can be used for inversion, which, added to the remarks made in Section 2, leads to a very poor vertical resolution of the retrieved stratospheric structure. Indeed, from these data only the general slope of the stratospheric profile can be inferred.

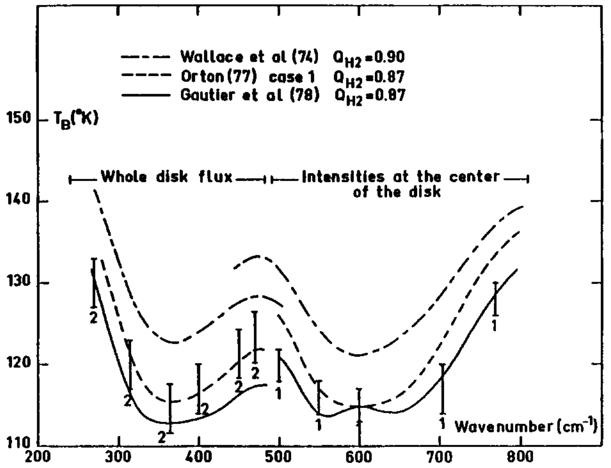

FIG. 3. Infrared spectra of Jupiter corresponding to the whole-disk flux in the range 200 to 500 cm^{-1} and to the intensity at the center of the disk in the range 500 to 800 cm^{-1}, calculated from the thermal profiles of Fig. 2. The spectrum, not shown for clarity, which corresponds to profile A, would be practically coincident with the spectrum labeled Gautier *et al.* (1979). Note that the data labeled 1 of Aumann and Orton (1976) correspond in fact to an effective cosine μ eff $= 0.82$; the spectrum corresponding to the Orton's profile would be in better agreement with data 1 if it had been calculated with μ eff $= 0.82$. The data labeled 2 are from Erickson *et al.* (1978).

The discrepancy between the three retrieved stratospheric profiles shown on Fig. 2 comes first from the different opacities used. The profile labeled by Gautier *et al.* (1979) was retrieved from the random band model described in Wallace *et al.* (1974). As analyzed by Orton (1977), the dependence upon frequency of such a band model is acceptable at low spectral resolution ($\simeq$20 cm^{-1}) in the range of 1220 to 1290 cm^{-1}. However, it is less accurate, especially for the temperature dependence, than a line-by-line opacity computation. The profile of Orton (1977) is obtained from a listing of the ν_4 band of CH_4 derived from the analysis of Taylor and Jones (1976) which was in disagreement with the results of Ko and Varanasi (1977), but there is now a general agreement that the conclusions of Taylor and Jones (1976) were erroneous. The line parameters compiled by Chedin *et al.* (1978) and the STRANSAC program (Scott, 1974; Chedin *et al.*, 1978) used to retrieve profile A fit perfectly well the high-resolution laboratory data of Ko and Varanasi (1977).

On the other hand, because of the low vertical resolution available from methane data (cf. Section 2) and of the high sensitivity to temperature of the Planck function at 7.7 μm, the computation of the Jovian flux in the center of the ν_4 band requires the knowledge of the temperature profile up to very high levels. Therefore, assumptions must be made on the thermal structure of the upper stratosphere. Orton (1977) has assumed a constant stratospheric gradient. Another possibility consists of introducing the thermal profile deduced from star occultation measurements (Hunten and Veverka, 1976; Combes *et al.*, 1975). However, if there is a general agreement between the authors concerning the estimate of the temperature at about 7×10^{-3} mbar (170 $\pm$ 20°K), there is some controversy concerning temperature values at deeper levels.

A technique of perturbation of the structure given by Combes *et al.* (1975) was applied in search of the temperature value at about the 0.1-mbar level which minimizes the r.m.s. of the residuals. Using the random band model leads to the profile labeled by Gautier *et al.*, while using the STRANSAC program leads to profile A. This result constitutes only one of the possible solutions. However, the following conclusions can be made in the case where the Jovian CH_4/H_2 mixing ratio is close to the solar ratio.

(a) An isothermal upper stratosphere at 170°K, as in the model proposed by Hunten (1976), is impossible to combine with the presently available ν_4 CH_4 Jovian spectrum.

(b) If a maximum in temperature exists at the 0.1-mbar pressure level, its value should not significantly exceed 200°K. A higher value is possible if the maximum is located at lower pressure levels, but, in this case, the negative gradient temperature required to reach 170°K at 7×10^{-3} mbar becomes very large. However, occultation measurements refer to the south-pole region and it cannot be excluded that the 7×10^{-3}-mbar temperature is warmer above the equator of Jupiter. At last, as analyzed by Orton (1977) a departure of the source function from LTE in the ν_4 band of CH_4 is possible at low pressure levels. In this case, temperatures significantly higher than 200°K at the 0.1-mbar level would be compatible with the 8-μm Jovian spectrum.

The comparison of these results with the modeling approach is obviously fundamental. The most sophisticated calculations in this way relative to Jupiter have been made by Wallace *et al.* (1974) who have computed a set of thermal models in the nongray case, introducing the solar absorption by all the near-infrared methane bands. They unfortunately chose an effective temperature value that was too high[1] in comparison to the experimental one so that they derived a troposphere that was too warm. As a consequence, the corresponding brightness temperature spectra do not fit the experimental far-infrared data (cf. Fig. 3). It is likely that a new computation of such a model with an effective temperature of 123°K, as recently given by Erickson *et al.* (1978) will lead to a troposphere more similar to those of the retrieved profiles shown in Fig. 2.

In the tropopause region, retrieved profiles and radiative models differ in respect to both the pressure level of the minimum temperature and the shape of the transition troposphere–stratosphere. Wallace and Smith (1978) point out the importance of this discrepancy since significant nonradiative processes should occur to produce the sharp transition observed on the retrieved profiles. However, as previously stated, the available information from the present 8-μm measurements allows us to infer only the general slope of the stratospheric profile, and the tropopause regions correspond to the pressure range where the information from the H_2–He opacity begins to vanish (cf. Fig. 5 of Orton (1977)). Therefore, we agree with Wallace and Smith (1978) that the tropopause pressure levels derived from inversion methods and from radiative models are all plausible. Such an ambiguity should be removed by the much more accurate and spectrally resolved measurements of the IRIS experiment aboard the two spacecraft of the Voyager Mission (Hanel *et al.*, 1977). On the other hand, the tropopause temperatures of the models of Wallace

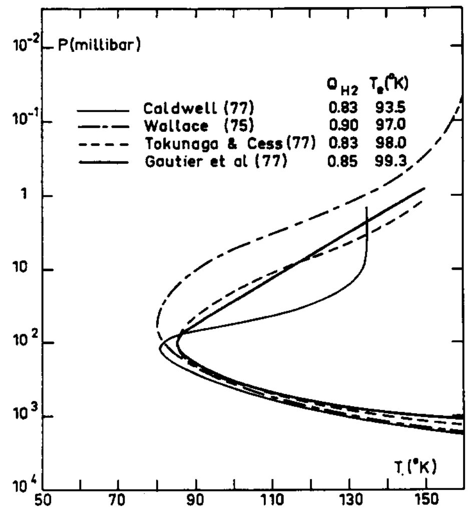

FIG. 4. Retrieved profile of Saturn from Gautier *et al.* (1977b) compared with the models of Wallace (1975b), of Caldwell (1977), and of Tokunaga and Cess (1977).

et al. (1974) seem definitely too warm to be able to fit the measurements of Aumann and Orton (1976) at the peak of the 600-cm^{-1} H_2 line (cf. Fig. 3).

In regard to the stratosphere, the agreement between retrieved profiles and the Wallace *et al.* modeling is more satisfactory (keeping in mind that the retrieved profile is a smoothing (a convolution) of the actual profile). Model B (not shown in Fig. 2), which includes the heating by all the near-infrared bands, is probably slightly too cold, but a model similar to Model C (Fig. 2), where some solar ultraviolet absorption by dust is introduced, should reproduce the behavior of profile A fairly well provided that the amount of stratospheric dust is slightly increased. The heating of the stratosphere by an ultraviolet absorber, first suggested by Axel (1972), thus seems verified.

A refinement of the modeling should be made by introducing the radiative cooling of the upper atmosphere due to ethane and acetylene. From Cess and Chen (1975), these hydrocarbon gases could reduce the temperature at the 0.1-mbar

[1] The value of 134°K announced by Wallace *et al.* (1974) is overestimated since the NH_3 pure rotation line absorption, which is predominant at $\lambda > 37$ μm, was omitted in their computations so that their derived far-infrared flux values are much too high. From our computations, the effective temperature corresponding to Model C of Wallace *et al.* (1974) is only 129°K, which is still too high compared to the experimental value.

level by as much as 20°K. Such a cooling then should be compensated by an aerosol heating more important than implied in Model C of Wallace *et al.* (1974).

B. Saturn

The main problem in determining the thermal structure of Saturn from infrared measurements comes from the large uncertainty caused by the evaluation of the ring emission at wavelengths greater than 30 μm. However at shorter wavelengths, direct measurements of the disk brightness are available.

A set of retrieved profiles have been obtained by Gautier *et al.* (1977b) from the far-infrared data shown on Fig. 5 and from the measurements of Gillett (1975) at 8 μm.

Besides the nominal profile shown on Fig. 4, Gautier *et al.* (1977b) have also retrieved cold profiles and warm profiles. The corresponding temperature spectra respectively fit the lower limit and the upper limit of the long wavelengths data (Fig. 5) derived from Armstrong *et al.* (1972). These profiles are plausible only if the spectral measurements of Saturn are considered. However, Caldwell *et al.* (1978a) have made drift scans of the equator of Saturn at four wavelengths between 17.8 and 22.7 μm. They have shown from the observed center-to-limb variations that only the nominal profile of Gautier *et al.* (1977b) and the very close model of Tokunaga and Cess (1977) (cf. Fig. 4) agree well with the data. This last model is calculated for a CH_4/H_2 mixing ratio of 7×10^{-4} and by assuming that 20% of the incident solar radiation is absorbed by stratospheric aerosols. It must be noticed that from our computations the effective temperature corresponding to this model is 98.7°K while Tokunaga and Cess announce 94°K. This discrepancy could signify that, because of the requisite approximations, the T_e parameter entering in the formulation of Tokunaga and Cess is not exactly the effective temperature. The model of Wallace (1975b) which exhibits a stratosphere clearly too cold implies that the stratospheric heating is only due to the near-infrared bands of methane (with $CH_4/H_2 = 7 \times 10^{-4}$). The model of Caldwell (1977), was calculated for a CH_4/H_2 mixing ratio of 2.1×10^{-3} and by assuming

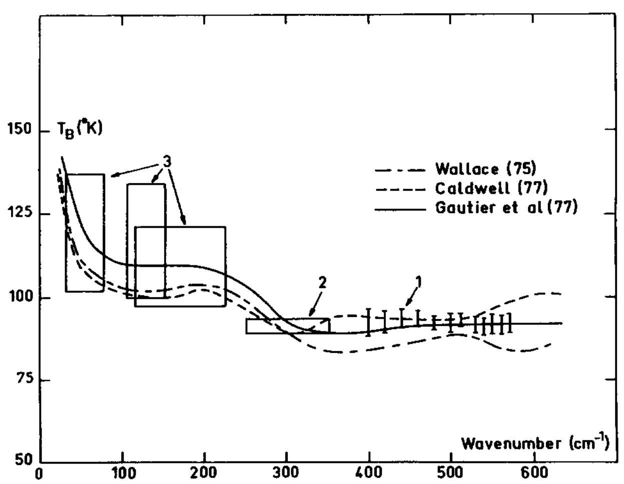

FIG. 5. Infrared spectra of Saturn calculated from the thermal profiles of Fig. 4. The spectrum derived from Tokunaga and Cess' model is not plotted since it is very close to the one calculated from the profile found by Gautier *et al.* Data 1 are from Tokunaga *et al.* (1977), data 2 are from Rieke (1975), and data 3 are derived from Armstrong *et al.* (1972).

that 11% of the incident ultraviolet solar radiation is absorbed by "Axel dust." It is likely that the too cold tropopause is due to the low assumed effective temperature (93.5°K) and not to the enhancement with respect to the solar value of the C/H mixing ratio.

On the other hand, Tokunaga *et al.* (1978) have deduced from north–south scans of Saturn between 17.8 and 22.7 μm that the temperature inversion is hotter at the south pole than at the equator. The equatorial model calculated by these authors is close to the global model of Tokunaga and Cess (1977) while their south pole thermal model exhibits a stratosphere warmer by about 5° to 7°K. These results contrast with the case of Jupiter, where the temperature profiles at various latitudes on the planet derived from Pioneer 10 and 11 radiometric experiments are quite similar (Orton and Ingersoll, 1976)[2]. No information is available on the upper stratosphere of Saturn.

As for Jupiter, the clouds' opacity could strongly influence the radiative transfer in the troposphere. Gillett and Forrest (1974) have suggested that the depression they observed in their Saturn spectrum at 9.5 μm was due to the ν_2 fundamental absorption band of solid NH_3. Slobodkin *et al.* (1978), from their analysis of the near-infrared spectrum of Saturn, also support the hypothesis of a Saturnian ammonia ice cloud. Caldwell (1977) has made an extensive analysis of this problem and a detailed modeling of the solid NH_3 ν_2 band. Calculating the outgoing planetary flux from a model including a thick cloud at a temperature level of 113.6°K overlaid by a NH_3 haze layer, he was able to fit the 9.5-μm depression quite well. Such a cloud model is also in qualitative agreement with the theoretical predictions of Weidenschilling and Lewis (1973). As in the Jupiter case, the problem is to know if the thick cloud is opaque to all wavelengths. If this is the case, the far-infrared brightness temperature spectrum of Saturn would be flat at wavelengths superior to 50 μm and incompatible with the warm data set used by Gautier *et al.* (1977) to retrieve their warm profile (this set includes data at 175 and 55 cm^{-1}, which correspond to the sounding of the troposphere). But as previously stated, this profile is unlikely. The nominal and cool data sets of Gautier *et al.* are still both plausible, although recent far-infrared observations of Saturn (Courtin *et al.*, 1979b) seem to favor the cool data set, and accordingly the tropospheric part of the cold profile retrieved by Gautier *et al.* (1977). New far-infrared and submillimetric observations of Saturn, including an accurate removal of the contribution of the rings are indispensable to determine the far-infrared emissivity of the Saturnian clouds.

[2] However, recent ground-based measurements of Jupiter made at 17.8 μm with a higher spectral resolution than the Pioneer measurements seem to lead to an opposite conclusion (Caldwell *et al.*, 1978b).

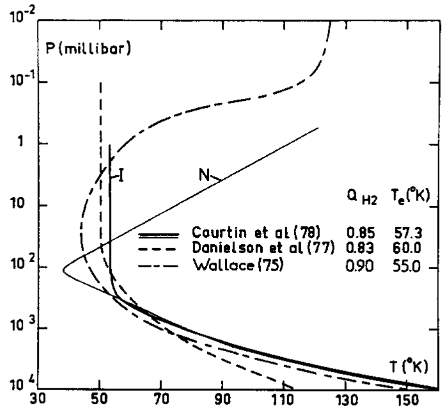

FIG. 6. Retrieved profiles of Uranus from Courtin *et al.* (1978) (I and N) compared with the models of Wallace (1975b) and Danielson *et al.* (1977).

C. *Uranus*

The infrared data relative to Uranus and Neptune are much more scarce and imprecise than for Jupiter and Saturn. Indeed,

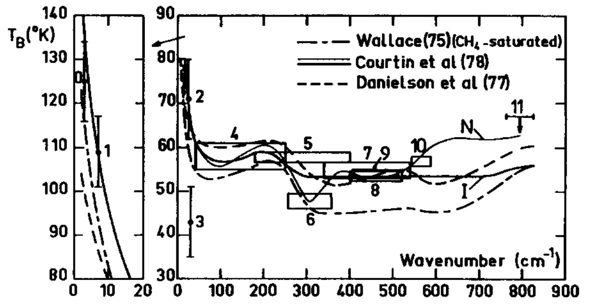

FIG. 7. Infrared spectra of Uranus computed from the profiles of Fig. 6. The left-hand rectangle shows the millimetric brightness temperatures. Data 0 are from Ulich and Conklin (1976); 1, Courtin *et al.* (1977); 2, Loewenstein *et al.* (1977); 3, Harper *et al.* (1972); 4, Fazio *et al.* (1976); 5, Loewenstein *et al.* (1977); 6, Low *et al.* (1973); 7, Morrison and Cruikshank (1973); 8, Rieke and Low (1974); 9 and 10, Gillet and Rieke (1977); and 11, Rieke and Low (1974).

measurements of Uranus which should correspond to similar atmospheric levels give different brightness temperatures so that very different profiles can be retrieved (Courtin *et al.*, 1978). They lead to brightness temperature spectra which only fit a part of the data well. The spectrum N shown in Fig. 7 corresponding to profile N of Fig. 6, is in good agreement with the set of the infrared measurements except the one made from aircraft by Loewenstein *et al.* (1977) in the spectral range 25 to 55 μm. But the heating of the stratosphere implied by a profile similar to profile N would require the presence of a strong absorber of the solar radiation in this atmospheric range. At tropopause temperatures of Uranus the methane should condense, but Wallace (1975b), assuming that methane distribution did not follow the saturation law, has calculated a "supersaturated" stratospheric profile very similar to the profile N in the stratosphere. However, in this case the spectrum of the ν_4 band of CH_4 at 7.7 μm should be clearly seen in emission. But Gillett and Rieke (1977) as well as Macy and Sinton (1977) were not able to detect Uranus in the 8-μm range. Thus, a warm stratosphere cannot be due to methane.

Another selection of data leads to the retrieval of profile I (Fig. 6). The corresponding spectrum (Fig. 7) is in good agreement with the set of experimental data except for those of Low *et al.* (1973) at 33.5 μm and of Gillett and Rieke (1977) at 17.7 μm. The CH_4-saturated thermal model of Wallace (1975b) probably would be close to profile I in the troposphere and the lower stratosphere if the model was calculated for an effective temperature of 57°K instead of the value of 55°K assumed by Wallace.

The infrared spectrum corresponding to the model of Danielson *et al.* (1977) satisfactorily agrees with the data except that the low-frequency part is in conflict with the observed millimetric brightness temperatures. This is due to the excessively large amount of methane in the deep layers assumed by the authors ($CH_4/H_2 > 1/30$), which causes the lapse rate to be much smaller than the one required to match the data. Thus, such an enhancement of methane compared to the solar abundance is unlikely in Uranus.

In regard to the stratosphere, there is no information available from infrared measurements, but the results of the occultation measurements of SAO 158687 by Uranus on March 10, 1977, indicate a temperature of about 100°K at pressure levels between 10^{-4} and 10^{-2} mbar (Dunham *et al.*, 1977), and is in good agreement with the values given by the saturated model of Wallace (1975b).

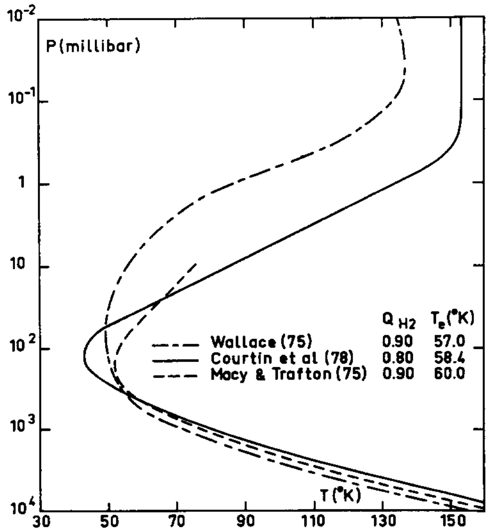

FIG. 8. Retrieved profile of Neptune from Courtin *et al.* (1979a) compared with the models of Wallace (1975b) and of Macy and Trafton (1975).

Because of the large inclination of Uranus's axis of rotation, very strong seasonal thermal effects are plausible on this planet, especially in the upper atmosphere. This point will be discussed in Section 4.

D. Neptune

In contrast with Uranus, the existence of a strong temperature inversion in the atmosphere of Neptune is certain.

The 1968 occultation of BD $-17°$ 4388 indicated a high temperature of nearly 140°K at pressure levels around 3×10^{-3} mbar (Wallace, 1975a). Then, ground-based infrared observations in the 17- to 28-μm atmospheric window, indicated the existence of a strong temperature inversion. Furthermore the ν_4 band of methane at 8 μm and the ν_9 fundamental band of ethane at 12.2 μm have been clearly detected in emission in the spectrum of Neptune. At tropopause temperatures of this planet, methane should be condensed so that its abundance in the stratosphere should be very weak. In this case, the only way to interpret the 8-μm spectrum would be to assume an extremely warm stratosphere, but as pointed out by Courtin *et al.* (1978) such a profile would not fit the 17.6-μm measurement of Gillett and Rieke (1977). Therefore, the interpretation of the set of the presently available infrared Neptunian data (Fig. 9) requires the presence in the stratosphere of a large amount of methane.

Courtin *et al.* (1979a) have retrieved a thermal profile of Neptune (Fig. 8) by assuming a CH_4/H_2 mixing ratio of 2.10^{-3} constant with altitude. A random band model was used to compute the CH_4 opacity. Using the more accurate line-by-line transmissions of Chedin *et al.* (1978) would lead, in order to retrieve the same

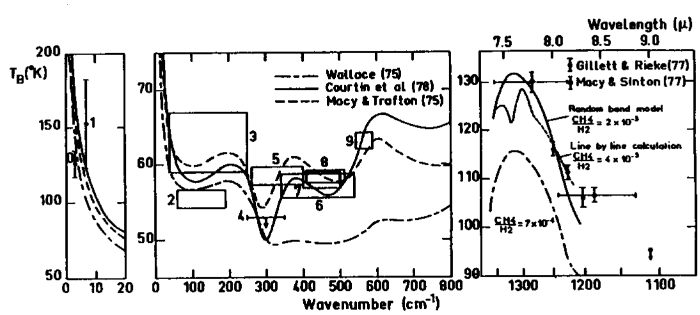

FIG. 9. Infrared spectra of Neptune computed from the thermal profiles of Fig. 8. The 8-μm emission spectrum of methane is represented at right. Data 0 are from Ulich and Conklin (1976); 1, Courtin *et al.* (1977); 2 and 5, Loewenstein *et al.* (1977); 3, Stier *et al.* (1977); 4, Low *et al.* (1973); 6, Morrison and Cruikshank (1974); 7, Rieke and Low (1974); and 8 and 9, Gillet and Rieke (1977).

TABLE I

Planet	T_e (°K)	$T_e^{\text{equil.}}$	Radiated power/ solar abs. power
Jupiter	123 ± 2	104 ± 3	2.0 ± 0.4^a
Saturn	99.3 ± 4.6	78 ± 3	2.6 ± 0.9
Uranus	57.3 ± 2.6	57 ± 1	$\leqslant 1.3$
Neptune	$58.4^{+7.4}_{-3.9}$	46 ± 2	$2.6^{+2.4}_{-0.9}$

[a] Taking the value T_e (equil.) = 109.4°K from Tomasko *et al.* (1978) would reduce the lower limit to 1.5.

profile, to the assumption of a CH_4/H_2 mixing ratio of 4×10^{-3}. Any diminution of the CH_4 mixing ratio leads to retrieve a warmer stratosphere.

Wallace (1975b) and Macy and Trafton (1975) have also assumed a CH_4 mixing ratio constant with altitude for computing thermal models of Neptune. The 7×10^{-4} CH_4 mixing ratio adopted by Wallace leads to a much too cold stratosphere resulting in too low brightness temperatures at wavenumbers superior to 300 cm^{-1} (Fig. 9), and also to a too cold 8-μm spectrum. Macy and Trafton (1975) have used several CH_4 mixing ratio values. The model shown in Fig. 8 which best agrees with the far-infrared experimental measurements (Fig. 9) was calculated for a CH_4 mixing ratio of 2×10^{-3} and an effective temperature of 60°K. It must be noticed that the tropopause of this model is too warm to be compatible with the upper limit given by Low *et al.* (1973) and that the lower stratosphere is too cold to fit well the 17.7-μm measurement of Gillett and Rieke (1977). Macy and Trafton have restricted their models to pressure lower than 10 mbar so that it was not possible to compare with the 8-μm spectrum.

For the troposphere, all the profiles shown in Fig. 8 are plausible because of the large uncertainty of the measurements at wavelengths greater than 50 μm.

Clouds certainly exist in the atmospheres of Uranus and Neptune (Weidenschilling and Lewis, 1973) but up to now there is no indication that they influence the thermal infrared spectrum of these planets.

4. THE RADIATIVE BUDGET OF THE GIANT PLANETS

In Table I, the measured values of the effective temperature of the giant planets are compared to the theoretical equilibrium values.

For Jupiter, Ingersoll *et al.* (1976) have derived from the Pioneer 10 and 11 infrared radiometers the value 125 ± 3°K. The profiles retrieved by Gautier *et al.* (1979) from the airborne measurements made by Aumann and Orton (1976) and by Erickson *et al.* (1978) correspond to an effective temperature of about 123°K, in agreement with the value 123 ± 2°K announced by Erickson *et al.* (1978).

Concerning Saturn, the determination of the effective temperature is much less precise than for Jupiter, because of the previously mentioned difficulty in estimating the ring contribution to the observed emission. The extreme values given in Table I correspond to the cold and warm retrieved profiles of Gautier *et al.* (1977b), but the higher value of 103.7°K is very unlikely since it would imply no contribution from the rings in the far-infrared range. Moreover, as mentioned in Section 3, the center-to-limb measurements of Caldwell *et al.* (1978a) exclude warm profiles. Therefore, the effective temperature is more likely between 94.6 and 99.3°K, corresponding to an internal heating source equal to at least 85% of the solar absorbed power and less than 200% of this quantity.

The difference between the cases of Uranus and Neptune is puzzling. Although the measurements giving the effective temperature of Neptune made by Loewenstein *et al.* (1977) and by Stier *et al.* (1977) are in conflict, the lower estimate of

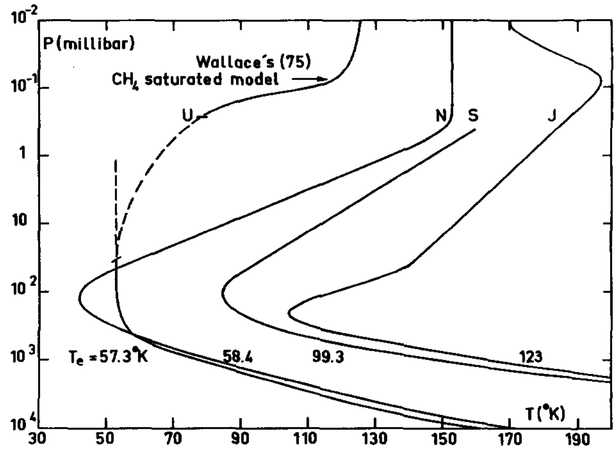

FIG. 10. Retrieved profiles of the four giant planets. For detailed explanations, see text.

Loewenstein *et al.*—53.2°K—indicates the existence of an internal heat source equal to at least 70% of the solar absorbed power.

For Uranus, there is no evidence of internal heat source. If it exists, it is not greater than about 34% of the solar absorbed heat flux if we adopt the albedo value of Dlugach and Yanovitsky (1974), (0.37 ± 0.05), or than 20% of the solar flux if we take the estimate of Danielson (1977).

Such a difference between Uranus and the three other giant planets was not precisely predicted in the previous published theories of the planetary interiors, but Podolak and Cameron (1974) indicate that, in order to match the observed values of the gravitational moment J, the interior of Neptune should be hotter than the one of Uranus. Such a difference could explain the discrepancy in the strengths of the internal sources if they are due to the slow cooling of the planetary interior.

Another possibility, first suggested by Danielson (1977), is that a heat sink could exist in the atmosphere of Uranus since the presently visible part of the southern hemisphere has been in darkness for 40 years and could not yet be warmed up. Macy and Trafton (1975) have pointed out that the Pioneer 10 and 11 experiments show that the polar and equatorial regions of Jupiter have very close effective temperature values (Ingersoll *et al.*, 1976). That implies the presence of a significant equator to pole transfer of heating. But the comparison with Uranus could be irrelevant since the atmospheric dynamics of the two planets are certainly very different, as pointed out by Stone (1973, 1975).

We have calculated that the radiative time constant of the Uranian atmosphere at the 2-bar pressure level—where most of the solar radiation should be absorbed—should be equal to about 600 Earth years, which is long compared to the orbital period of 84 years and should minimize any seasonal effects. However, the radiative time scale decreases with the pressure and would become equal to Uranus's orbital period at the 200-mb level (Stone, 1973). The effective temperature of Uranus is mainly determined by the flux emitted between 50 and 250 cm^{-1}. As seen in Fig. 1, the Uranian emission in this spectral range mainly comes from about the 500-mbar pressure level. Therefore, despite the moderating effect of the deep layers mentioned by Stone (1975), seasonal variations of the effective temperature are possible (and accordingly, variations of the atmospheric thermal profile). In this case, repeated observations of the far-infrared spectrum of Uranus in the future years would give the answer to the problem.

A more detailed analysis has been recently given by Hubbard (1978). From a convective cooling model of Uranus and Neptune interiors, this author studied the thermal evolution of these planets as a function of time. In his model, the internal heat of the two planets is derived from the radiation of primordial heat, but the solar radiation received by Uranus tends to suppress the rate of emission of interior flux, while this is not the case for Neptune which receives about 2.4 times less solar energy than Uranus. Hubbard calculates the variation of the effective temperature as a function of time for both planets. For a common age (4×10^9 years) of the two planets, he deduces an effective temperature value of 53°K for Neptune and of 60°K for Uranus. Although these results are only in marginal agreement with the lower limit for Neptune and the upper limit for Uranus (cf. Table I), they are impressive if we consider the uncertainties on the internal structure parameters. More accurate determinations of the effective temperatures of Uranus and Neptune would greatly improve our understanding of the question.

5. CONCLUSION

To conclude, the recent spectral measurements of the infrared radiances emitted by the giant planets, combined with appropriate techniques of inversion of the radiative transfer equation, have led to a significant improvement in the knowledge of their atmospheric thermal structures. The profiles shown in Fig. 10 are plausible "working" models of the atmospheres of the giant planets. We emphasize again that obviously these profiles are not the actual profiles but they represent the simplest thermal structures which lead to brightness temperatures and effective temperature values fitting the experimental data. They should not be considered in conflict with models which exhibit some finer thermal structure provided that these models also fit the experimental data.

While the tropospheres of these planets are relatively well determined, at least for Jupiter, presently retrieved stratospheric profiles should be considered as rough approximations since the vertical resolution in this atmospheric range is very poor. For Uranus, where no information on the upper stratosphere can be obtained from infrared measurements, we propose a composite model where the tropospheric part is the retrieved profile I and the stratospheric part is the saturated model of Wallace.

Great progress in the determination of the Jovian and Saturnian thermal structures is expected from the coming IRIS experiment aboard the two Voyager spacecraft. The thermal profiles will be retrieved almost everywhere on the planetary disks from the spectra of Jupiter and Saturn measured from 2.5 to 50 μm (Hanel *et al.*, 1977).

Uranus and Neptune still appear to be rather mysterious. The first problem is to understand why the amplitude of the Uranian internal heat source, if there is any, does not exceed 34% the solar absorber power, a value which is much less than those measured for the three other planets. A second problem is the apparent existence of a warm stratosphere in Neptune which seems to imply the presence in this atmospheric range of an amount of methane much greater than the one implied by the saturation law.

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