GCA-TR-70-9-N

PLANETARY METEOROLOGY

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FACILITY FORM 602

N70-42710
(ACCESSION NUMBER)
(THRU) 1

54
(PAGES)

CR-114158
(NASA CR OR TMX OR AD NUMBER)

(CODE) 30
(CATEGORY)

GCA
CORPORATION
Bedford, Massachusetts

FINAL REPORT

CONTRACT NO. NASw-1725

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HEADQUARTERS
Washington, D. C.

August 1970

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by George Ohring

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GCA TECHNOLOGY DIVISION
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By George Ohring, GCA Corporation, GCA Technology Division,
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SUMMARY

This final report reviews research performed during the past two years under NASA Contract NASw-1725, entitled Planetary Meteorology. Since the first year's research was reported in full in an annual technical report, only abstracts of this work are published in this report. This work included the following investigations:

High Surface Temperature on Venus: Evaluation of the Greenhouse Explanation

Mean Vertical Temperature Profile of the Venusian Atmosphere: Theoretical Calculations Based upon Radiative Equilibrium

Infrared Transmittance Model for Planetary Atmospheres Research: Empirical Fits to Plass' CO_2 and H_2O Infrared Transmittance Tables

During the second year of the contract the primary emphasis was on the temperature climate of Venus. A theoretical estimate of the temperature climate of Venus is obtained with the use of a thermal (radiative-convective) equilibrium model. Emission of infrared radiation and absorption of solar radiation by carbon dioxide and water vapor are considered in the calculations and are computed with a non-grey transmittance model. It is found that a model atmosphere with a water vapor mixing ratio of 10^{-3} yields low latitude temperature profiles in good agreement with the spacecraft temperature profiles. Thus, a water vapor mixing ratio of 10^{-3} is adopted for calculations of temperature profiles for different latitudes on Venus. Based upon these calculations, a temperature cross-section through the atmosphere of Venus, from the equator to 80° latitude, and from the surface to a pressure level of 0.02 atm, is presented.

Additional research during the second year included an evaluation, using a meteorological approach, of the hypothesis that the clouds of Venus are composed of water substance. Basically, best estimates of temperature profiles are used to obtain required saturation water vapor amounts. Actual water vapor amounts, based upon information from spacecraft and earth-based observations, are then compared to the required amounts to see if saturation is achieved. The results indicate that the Soviet Venera 4, 5, and 6 water vapor observations support the hypothesis of H_2O clouds. The earth based spectroscopic observations of water vapor

amount may or may not be compatible with H_2O clouds depending upon: (1) the amount observed spectroscopically - which varies with time, (2) how the water vapor is distributed with altitude above the cloud-top, and (3) the exact temperature in the vicinity of the cloud-top.

SECTION I

INTRODUCTION

This final report covers two years of research on the subject of Planetary Meteorology. The major subject during the two-year period was the planet Venus, and in particular the thermal structure of the planet's atmosphere. As in our previous work on the meteorology of the planets, the basic approach was to combine available observational data with meteorological theory to improve our understanding of a planet's atmosphere. In the research reported in this final report, much of the observational data resulted from the successful space probes to Venus - the American Mariner 5 and the Soviet Veneras 4, 5, and 6. It is only through such a combination of new observational data with sound theoretical reasoning and interpretation that rapid and solid advances can be made in our knowledge of the meteorology of the planets.

During the first year of the contract we were able to show, with a non-grey radiative transfer model, that the observed high surface temperatures could be produced by a large atmospheric greenhouse if certain conditions were met. Most vital of these conditions was a water vapor mixing ratio of $\sim 10^{-3}$ or more. This is within the range of water vapor mixing ratios reported by the Soviet spacecraft Veneras 4, 5, and 6 but well below the water vapor mixing ratios observed spectroscopically.

Having established that a greenhouse effect could maintain the observed surface temperature, we then proceeded to calculate the vertical temperature profile with the use of a non-grey radiation model and the assumption of thermal (radiative-convective) equilibrium. Computed profiles agree well with the temperatures observed by the Mariner 5 and Veneras 4, 5, and 6 spacecraft for model atmospheres with water vapor mixing ratios of order 10^{-3}. Preliminary estimates of the temperature climate on Venus are presented, based upon these calculations.

In addition to the work on temperatures on Venus, a study was performed to determine if the observational indications of water vapor amounts on Venus were compatible with the water vapor amounts required for saturation. This was a meteorological approach to the evaluation of the hypothesis that the Venusian clouds are made of water substance.

Research conducted during the first year of the contract is summarized in Section II. The work on the theoretical calculations of the temperature climate on Venus may be found in Section III. The evaluation of the hypothesis that the clouds of Venus are water is contained in Section IV.

SECTION II

SUMMARIES OF RESEARCH PREVIOUSLY REPORTED UPON

A. Introduction

The results of research performed during the first year of the contract have already been completely reported. Hence, rather than reprinting this material in this final report, we present here only summaries of research topics covered during the first year of the contract, and indicate where the full reports have been published. The interested reader may easily obtain copies of the full reports.

B. High Surface Temperature on Venus: Evaluation of the Greenhouse Explanation

The full details of this research have appeared in the following references:

Ohring, G., 1969: High surface temperature on Venus: Evaluation of the greenhouse explanation, Icarus, 11, 171-179.

Ohring, G., 1969: Studies in Planetary Meteorology, Ann. Tech. Rpt., NASA Contract No. NASw-1725, GCA-TR-69-8-N, 91 pp.

We present here a summary of this research.

SUMMARY

Calculations of the mean surface temperature of Venus are performed with a simple non-grey radiation balance model. The model is based upon a balance of net incoming solar radiation and emerging thermal radiation at the top of the atmosphere. To calculate the emerging thermal radiation, it is assumed that the shape of the vertical temperature profile is similar to that observed by Mariner 5 and Venera 4 - that is, a constant lapse-rate of 9°C/km from the surface to a pressure level of a few tenths of an atmosphere, above which the temperature remains constant. Given the atmospheric composition and surface pressure, the surface temperature can be determined from the balance requirement at the top of the atmosphere. Calculations are performed for a low surface pressure (20 atm) and high surface pressure 65 atm) model. For a pure carbon dioxide atmosphere, the results indicate that mean surface temperatures of 500°K to 550°K can be maintained in the 20 atm model, and 600°K to 650°K in the 65 atm model, if water vapor mixing ratios are of the order of 10^{-3}.

C. Mean Vertical Temperature Profile of the Venusian Atmosphere: Theoretical Calculations Based Upon Radiative Equilibrium

This research has been reported in full in:

Ohring, G., 1969: Studies in Planetary Meteorology, Ann. Tech. Rpt., NASA Contract No. NASw-1725, GCA-TR-69-8-N, 91 pp.

Only a summary is presented here.

SUMMARY

Mean radiative equilibrium temperature profiles are calculated for the Venusian atmosphere. It is assumed that the equilibrium is the result of gaseous absorption and emission, and a non-grey transmittance model is used. The equilibrium temperatures are computed with an iteration technique. The assumed model atmosphere consists of 100 percent carbon dioxide with a trace - 10^{-5} - of water vapor. Calculations are performed for two surface pressure models - 20 atm and 65 atm. For the 20 atm model, the computed radiative equilibrium surface temperature is 490°K; for the 65 atm model, 676°K. The radiative equilibrium temperature profile for the 65 atm model is in general agreement with the observational indications of the Venusian temperature profile, but is convectively unstable in its lower layers.

D. Infrared Transmittance Model for Planetary Atmospheres Research: Empirical Fits to Plass' CO_2 and H_2O Transmittance Tables

This research has been reported in full in:

Ohring, G., 1969: Studies in Planetary Meteorology, Ann. Tech. Rpt., NASA Contract No. NASw-1725, GCA-TR-69-8-N, 91 pp.

Only a summary is presented here.

SUMMARY

Transmittance tables for carbon dioxide and water vapor, computed from a quasi-random band transmission model by Plass and co-workers, are fit, by least squares techniques, to a generalization of the strong line absorption law. The fits are for 100 cm^{-1} intervals, from 600 cm^{-1} to 10,000 cm^{-1} for CO_2, and from 1000 cm^{-1} to 10,000 cm^{-1} for H_2O. For CO_2, the path length range covered is 10^3 to 2.37×10^7 atmo-cm, and the pressure range is 0.1 to 31 atm. For H_2O, the path length range

covered is 10^{-3} to 50 precipitable cm, and the pressure range is 0.1 to 1 atm. Comparison of the empirical fits with the original data indicates that the path length and pressure dependence of the transmittance are being fit quite well, but that the temperature dependence could be improved upon. The overall root-mean-square difference between empirically fit and original transmittances is 0.10.

SECTION III

THE TEMPERATURE CLIMATE OF VENUS

A. Introduction

The expression temperature climate refers to the major spatial and temporal variations of temperature on the surface and in the atmosphere of a planet. On the Earth, for example, the major spatial variations are latitudinal and vertical, and the major temporal variations are seasonal. Superimposed on these variations are longitudinal variations due to land-sea and topographical effects, interdiurnal variations due to travelling storms, and day-night variations. On Venus, since the inclination of the planet is close to 0°, we would expect no seasonal variations. Thus, the major variations on Venus are probably latitudinal and vertical, with a possible modulation due to day-night differences, the effects of an inhomogeneous surface, and travelling weather systems.

In the research summarized here, an attempt is made to simulate the temperature climate of Venus, by synthesizing the results of theoretical calculations and available observations. The theoretical calculations are based upon a thermal equilibrium model that includes the effects of convection as well as radiation on the vertical temperature structure. These theoretical calculations provide a preliminary estimate of the temperature climate of Venus. The importance of diurnal variations is analyzed theoretically and observationally. Comparison of the temperature climate model with available space probe observations of Venusian temperature profiles yields good agreement. The modification of the thermal equilibrium temperatures by horizontal heat transport due to the atmospheric circulation is discussed.

B. Thermal Equilibrium Model

Under conditions of thermal equilibrium, the temperature profile must satisfy the following requirements.

(1) At the surface, there is a balance between the radiative energy gain and the convective energy loss.

(2) In the convective region (troposphere), there is a balance in each layer between radiative losses and convective gains.

(3) In the radiative equilibrium region (stratosphere), there is a balance in each layer between absorption of solar radiation and emission of infrared radiation.

An iterative scheme is used to approach the thermal equilibrium temperature profile. In this scheme, we start with an assumed temperature profile; compute the radiative fluxes; correct the temperatures with iteration equations based upon an approach to radiative equilibrium; correct for superadiabatic layers; and continue iterating until the requirements for thermal equilibrium are satisfied.

We assume that the important radiative processes are gaseous absorption and emission. The upward and downward infrared fluxes of radiation at a reference level i in a spectral interval r can be written as

$$F_r(i)\uparrow \;=\; B_r(s)\;\;\tau_r(i,1) + \int_{\tau_r(i,1)}^{1} B_r\; d\tau_r \tag{1}$$

$$F_r(i)\downarrow \;=\; \int_{\tau_r(i,N1)}^{1} B_r\; d\tau_r \tag{2}$$

where B_r is the black-body flux in the spectral interval, τ_r is the flux transmittance of the spectral interval, 1 refers to the planet's surface, N1 to the top of the atmosphere. $\tau_r(i,1)$ represents the transmittance of the layer between the surface and level i; $\tau_r(i,N1)$ represents the transmittance between the top of the atmosphere and level i. A schematic illustration of the division of the atmosphere into layers for numerical integration of Equations (1) and (2) is shown in Figure 1. The total infrared flux at level i, $F_{net}(i)$, is obtained by summing (1) and (2) over all spectral intervals and subtracting the downward flux from the upward flux.

$$F_{net}(i) = \sum F_r(i)\uparrow \;-\; \sum F_r(i)\downarrow \tag{3}$$

The solar radiation intensity at level i in the spectral interval r is given by

$$I_r(i) = I_r(N1)\;.\;\cos\xi\;.\;\tau_r(i,N1)\;.\;(1-A) \tag{4}$$

where $I_r(N1)$ is the solar radiation intensity in spectral interval r at the top of the atmosphere, ξ is the zenith angle of the sun, and A is

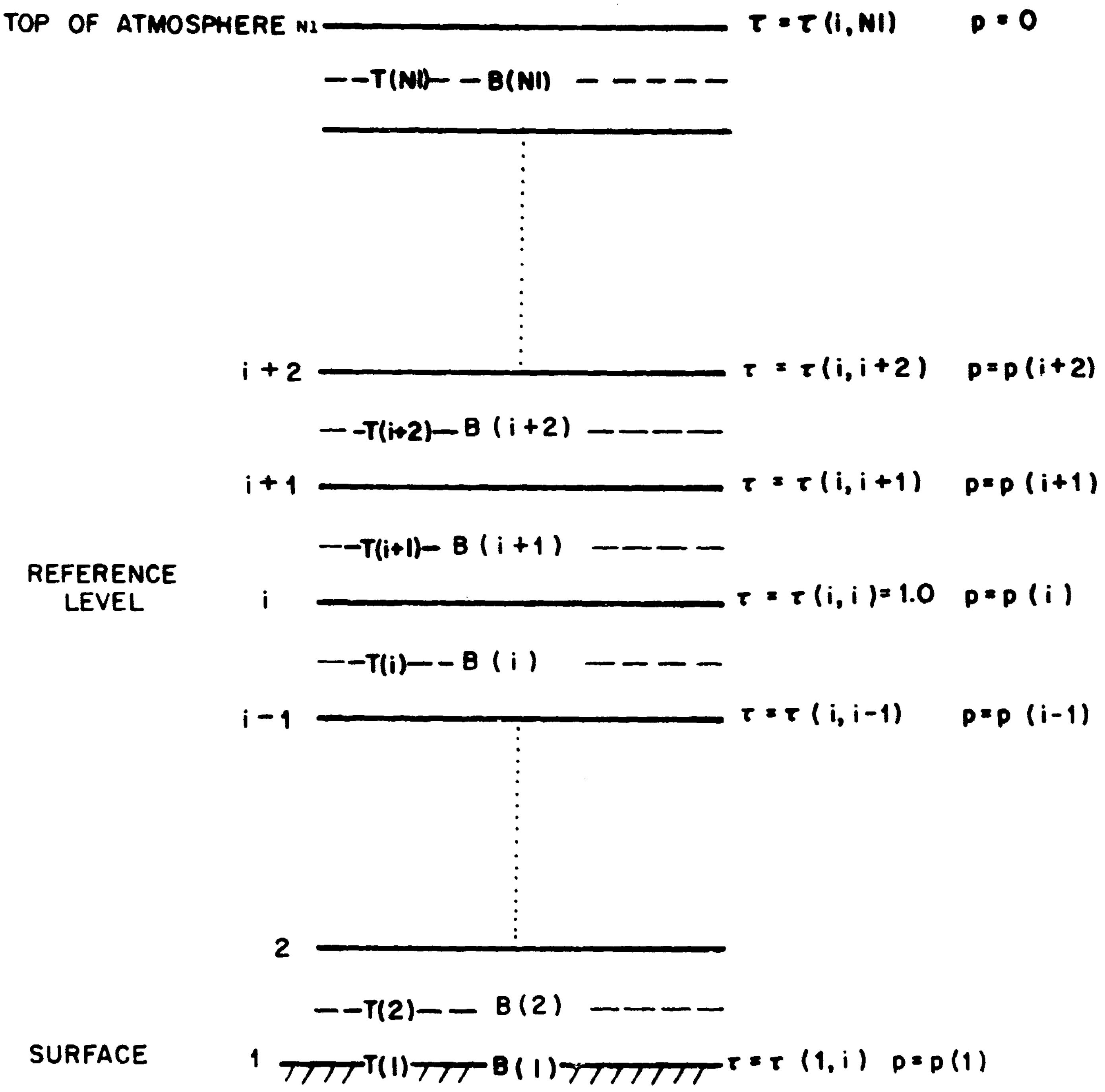

Figure 1 Schematic illustration of division of atmosphere into layers.

the planetary albedo. $\tau_r(i,N1)$ in the solar radiation calculation is computed for the slant path. The total intensity of solar radiation at i, I(i), is obtained by summing over all intervals of the solar spectrum.

$$I(i) = \sum I_r\ (i) \tag{5}$$

We approach the thermal equilibrium temperature profile using iteration equations based upon an approach to pure radiative equilibrium and correcting at each iteration for the effects of convection. In pure radiative equilibrium , the net infrared flux balances the solar radiation intensity at each level in the atmosphere.

$$F_{net}(i) = I(i) \tag{6}$$

The solar radiation flux, I(i), is not a function of temperature (except for a minor effect due to the temperature dependence of the transmittance) and can thus be computed once and for all for a particular solar zenith angle, albedo, and atmospheric composition and pressure. At radiative equilibrium, $F_{net}(i)$ must equal I(i), as shown in Equation (6). Thus, we know the radiative equilibrium values of $F_{net}(i)$. Based upon this information, we can develop an iteration procedure for driving the temperatures toward their radiative equilibrium values. For purposes of our iteration procedure, we assume that the net infrared flux at the level i is due mainly to the radiation fluxes emitted by the layers adjacent to i , and, further, that the emission is proportional to the fourth power of the temperature. Thus, for our correction procedure, we assume

$$F_{net}(i) \sim \left[T(i)^4 - T(i+1)^4\right] \tag{7}$$

This assumption leads to the following correction procedures for correcting a temperature profile at iteration n to a temperature profile at iteration n+1.

$$\left(\overset{n+1}{T(N1)}\right)^4 = \left(\overset{n}{T(N1)}\right)^4 \times \left[I(N1)/F{\uparrow}^{n}(N1)\right] \tag{8}$$

and

$$\left(\overset{n+1}{T(i)}\right)^4 = \left(\overset{n+1}{T(i+1)}\right)^4 + \left[\left(\overset{n}{T(i)}\right)^4 - \left(\overset{n}{T(i+1)}\right)^4\right] \times \left|I(i)/\overset{n}{F}_{net}(i)\right| \tag{9}$$

A new temperature at iteration (n+1) at the top layer, N, of the atmosphere, is computed from correction Equation (8). New temperatures at iteration (n+1) at successive lower layers i in the atmosphere are computed from correction Equation (9). As temperatures are computed, they are checked to determine if the computed temperature has resulted in a lapse-rate that is greater than the adiabatic lapse-rate. If so, the computed temperature is changed to the adiabatic temperature. The temperature at the next lower level is computed from (9), the same check is made, and so on until the surface is reached. This new temperature profile is checked to determine whether each layer is in radiative equilibrium with a stable lapse-rate, or is in adiabatic equilibrium. The outgoing infrared flux is checked to see if it balances the net incoming solar radiation at the top of the atmosphere. If all checks are positive, this temperature profile is in thermal equilibrium and satisfies the requirements listed above. If all checks are not positive, a new iteration is performed. A convergence criterion, ϵ, of 1 percent, or better, in the radiative region, is used in the calculations. That is,

$$\frac{F_{net}(i) - I(i)}{I(i)} \leq \epsilon \leq 1\% \qquad (10)$$

in the radiative region.

Although the assumed dependence of net infrared flux on temperature in the iteration procedure is theoretically valid only for optically thick, grey atmospheric layers, the scheme also works well on non-grey atmospheric layers of moderate infrared opacity.

Absorption and emission by carbon dioxide and water vapor are considered in the calculations. We adopt the transmittance model of Bartko and Hanel (1968), which is based upon strong line fits to available laboratory and theoretical transmittance data. In this model, the wavenumber range 0 to 8000 cm^{-1} is divided into 17 spectral intervals. Absorption of solar radiation takes place in spectral interval 16 (2000 to 2600 cm^{-1}) and spectral interval 17 (2600 to 8000 cm^{-1}). At wavenumbers greater than 8000 cm^{-1} it is assumed that no solar energy is absorbed in the atmosphere. All seventeen spectral intervals contribute to the infrared emission.

C. Numerical Integration Procedures

The basic formula used for computing the fluxes in each spectral interval is of the form

$$\int B \, d\tau = \Sigma B \Delta\tau \qquad (11)$$

where B is the black-body flux based upon the mean temperature of each layer and τ is transmittance. To compute the downward flux at the reference level i (see Figure 1), one must sum the contributions to (11) from the layers above i. If the layers are optically thick, most of the contribution to the summation will come from the first layer immediately adjacent to the reference level, which is given by

$$B(i+1)\left[1-\tau(i,\ i+1)\right] \tag{12}$$

where $\tau(i,\ i+1)$ is the transmittance of the layer bounded by levels i and i+1. The variation of transmittance with path length is essentially exponential and if this layer is optically thick, (12) will result in a relatively large error in the approximation to the integral - unless the layer in question is isothermal. One can improve the accuracy by simply increasing the number of layers until no layer is optically thick. But this increases the amount of computing time required. To resolve this computing problem, we have developed a scheme to integrate analytically, in an approximate way, the contribution from the first layer adjacent to the reference level.

The contribution from the first layer to the integral for the downward flux in a single spectral interval at the reference level i is

$$\int_{\tau(i,\ i+1)}^{1} B\,d\tau = \int_{p(i+1)}^{p(i)} B(p)\,\frac{d\tau}{dp}\,dp \tag{13}$$

where p is pressure.

From the equations for absorption and absorber path length given by Bartko and Hanel (1968), one can derive the following expression for transmittance

$$\tau\Big[\Big(p,\ p(i)\Big] = \exp\left\{-\left[h\left|p-p(i)\right|\left(\frac{p+p(i)}{2\,p_o}\right)^{k}\right]^{k/2}\right\} \tag{14}$$

where h is a constant for a particular spectral interval and layer of atmosphere, k is a constant for a particular spectral interval (the values of k are given in Bartko and Hanel, 1968), and p_o is standard pressure. Since we are concerned only with the first layer immediately adjacent to p(i), let us assume that p in the pressure correction term is equal to p(i). Let us further assume that k = 1, regardless of spectral interval, a reasonably good approximation for most spectral intervals. With these assumptions, we can write (14) as

$$\tau\left[p,\ p(i)\right] = \exp\left\{-\left[b\,|p - p(i)|^{\frac{1}{2}}\right]\right\} \qquad (15)$$

where

$$b = \left[h\ p(i)/p_g\right]^{\frac{1}{2}}.$$

We can write an expression for $d\tau/dp$

$$\frac{d\tau}{dp}\left[p\ ,p(i)\right] = -\ .5\ b\,|p - p(i)|^{-\frac{1}{2}} \exp\left\{-\left[b\,|p-p(i)|^{\frac{1}{2}}\right]\right\} \qquad (16)$$

Since values of τ are computed for all levels, including levels i and i+1, the values of b for each spectral interval and layer can easily be computed from application of (15) to the layer bounded by levels i and i+1,

$$b = -\ \frac{\ln \tau\left[p(i+1),\ p(i)\right]}{|p(i+1)-p(i)|^{1/2}} \qquad (17)$$

For the function B(p) in equation (13), we assume that

$$B(p) = B\left[\ p(i)\ \right] + c\,|p-p(i)| \qquad (18)$$

Using equations (16) and (18), we can write equation (13) as

$$\int_{\tau(i,i+1)}^{1} B\ d\tau = -\int_{p(i+1)}^{p(i)}\left[B(p(i)) + c\,|p-p(i)|\right]0.5\,b\,|p-p(i)|^{-\frac{1}{2}}\exp\left[-b\,|p-p(i)|^{\frac{1}{2}}\right]dp \qquad (19)$$

With the substitution $X = |p-p(i)|^{\frac{1}{2}}$, equation (19) becomes

$$\int_{\tau(i,i+1)}^{1} B d\tau = -b \int_{X(i+1)}^{o} \left[B(o) + c X^{2} \right] e^{-bX} dX \qquad (20)$$

where $X(i+1) = |p(i+1) - p(i)|^{\frac{1}{2}}$.

Equation (20) can be integrated analytically to yield

$$\int_{\tau(i,i+1)}^{1} B d\tau = B(o)\left(1-e^{-b\, X(i+1)} \right) - c\, e^{-b\, X(i+1)} \times \left[X(i+1)^{2} + \frac{2}{b} \left(X(i+1) + \frac{1}{b} \right) \right] + \frac{2c}{b^{2}} \qquad (21)$$

This represents an analytic approximation of the contribution of the first layer adjacent to level i to the downward infrared flux in a single spectral interval at the level i. Equation (21) is used with each spectral interval, the values of b being determined from Equation (17) applied to the layer bounded by levels i and i+1. The contribution to the upward infrared flux from the layer adjacent to and below level i is obtained in a similar manner. For the upward flux, the value of c in a layer is the negative of the value of c used in the computation of the downward flux. The contributions to the flux at level i from the other layers of the atmosphere are computed as before, from $\Sigma\, B\Delta\tau$. In most calculations the atmosphere is divided into ten layers of equal $\Delta\, \ell n/p$.

In another step to reduce computing time, the summation $\Sigma\, B\Delta\tau$ is stopped when τ becomes less than τ(minimum), where τ(minimum) is currently set at 10^{-4}. This step has a negligible effect on accuracy but reduces computing time considerably since much fewer τ's have to be calculated and used in the summation.

D. Results of Thermal Equilibrium Temperature Calculations

Prior to applying the thermal equilibrium model to the problem of the Venusian temperature climate, it is of interest to compare a thermal equilibrium temperature profile with a pure radiative equilibrium profile. Such a comparison is shown in Figure 2, in which both temperature profiles were computed for the following conditions: water vapor mixing ratio of 10^{-5}, carbon dioxide percentage of 100 percent, surface pressure

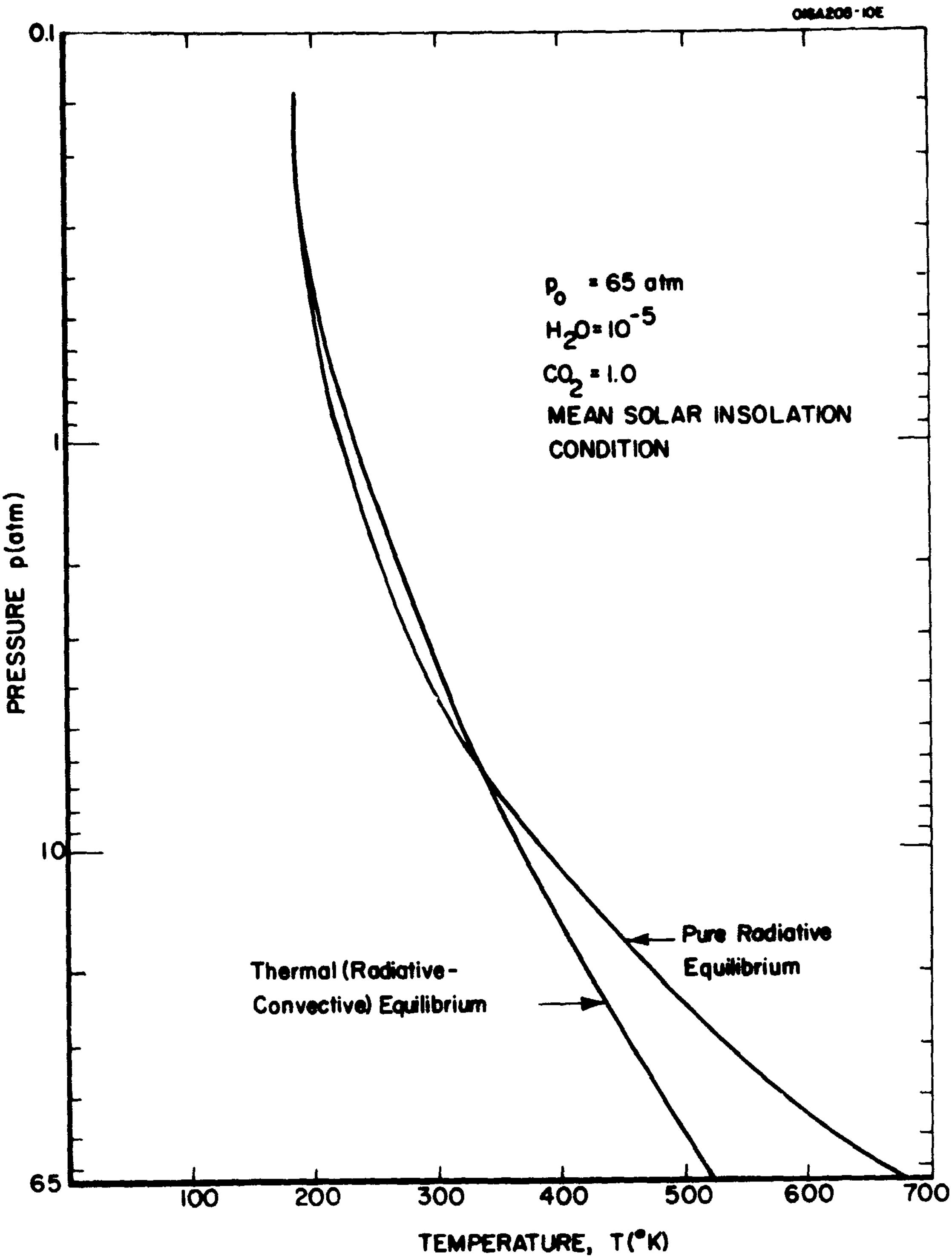

Figure 2. Comparison of thermal equilibrium and radiative equilibrium temperature profiles for Venus.

of 65 atm, planetary albedo of 0.73, mean solar insolation, and convective lapse-rate of 9°C/km. The major effect of convection is to reduce the surface temperature by 150°K, from 675°K in the pure radiative equilibrium case to 525°K in the thermal equilibrium case. Thus, estimates of Venusian surface temperatures based upon radiative equilibrium are liable to be in error by this amount.

Some of the physical parameters of the Venusian atmosphere are somewhat uncertain at the present time. The most important ones, in terms of their bearing on thermal equilibrium calculations are the water vapor content, the surface pressure, and the carbon dioxide content of the atmosphere. To determine the effects of these parameters on the temperature profile and to assist in the choice of a model atmosphere for further calculations of the temperature climate, a series of thermal equilibrium temperature profiles was computed for a range of these parameters.

Probably the greatest uncertainty, in terms of effects on the temperature profile, lies in the water vapor concentration. The Earth-based spectroscopic observations indicate water vapor mixing ratios of 10^{-4} to 10^{-6} (see, for example, Belton, 1968), whereas the Soviet Venera 4, 5, and 6 spacecraft observations indicate mixing ratios of 10^{-2} to 10^{-3}. (Vinogradov, et al., 1968; Avduevsky et al., 1970). This discrepancy could be resolved, if the spectroscopic observations refer to the upper atmosphere and the Venera observations to the lower atmosphere. To evaluate the effect of such uncertainties, a set of calculations of the temperature profile was performed for a range of mixing ratios, w, from 10^{-5} to 10^{-3}. The results are plotted in Figure 3.

For these calculations, a model atmosphere with surface pressure of 65 atm, CO_2 percentage of 100 percent, planetary albedo of 0.73, and convective lapse-rate of 9°C/km is used. Mean solar insolation conditions are assumed, for which the cosine of the solar zenith angle is 0.25. The results show a variation of surface temperature from 520°K to 715°K as the water vapor mixing ratio increases from 10^{-5} to 10^{-3}. The computed tropopause height (horizontal dash) varies from about 0.4 atm for $w = 10^{-5}$ to about 0.05 atm for $w = 10^{-3}$. The temperature profile for an H_2O mixing ratio of 10^{-3} is the one that agrees best with the mean surface temperature of ~700°K deduced from microwave observations. These calculations lend support to the Soviet observations of the water vapor content. In further calculations, we shall therefore assume a water vapor mixing ratio of 10^{-3}.

To evaluate the sensitivity of the temperature profile to surface pressure, a series of thermal equilibrium calculations was performed for surface pressures ranging between 10 and 100 atm. The surface pressure originally reported by Venera 4 for Venus, 20 atm (Avduevsky et al., 1968), is now known to be incorrect. The pressure of 20 atm reported by Venera 4 refers not to the surface of the planet but to a level some 20 to 25 km above the surface. Extrapolation of the Venera 4 observations to the surface of the planet yields a much higher pressure, ~ 65 atm

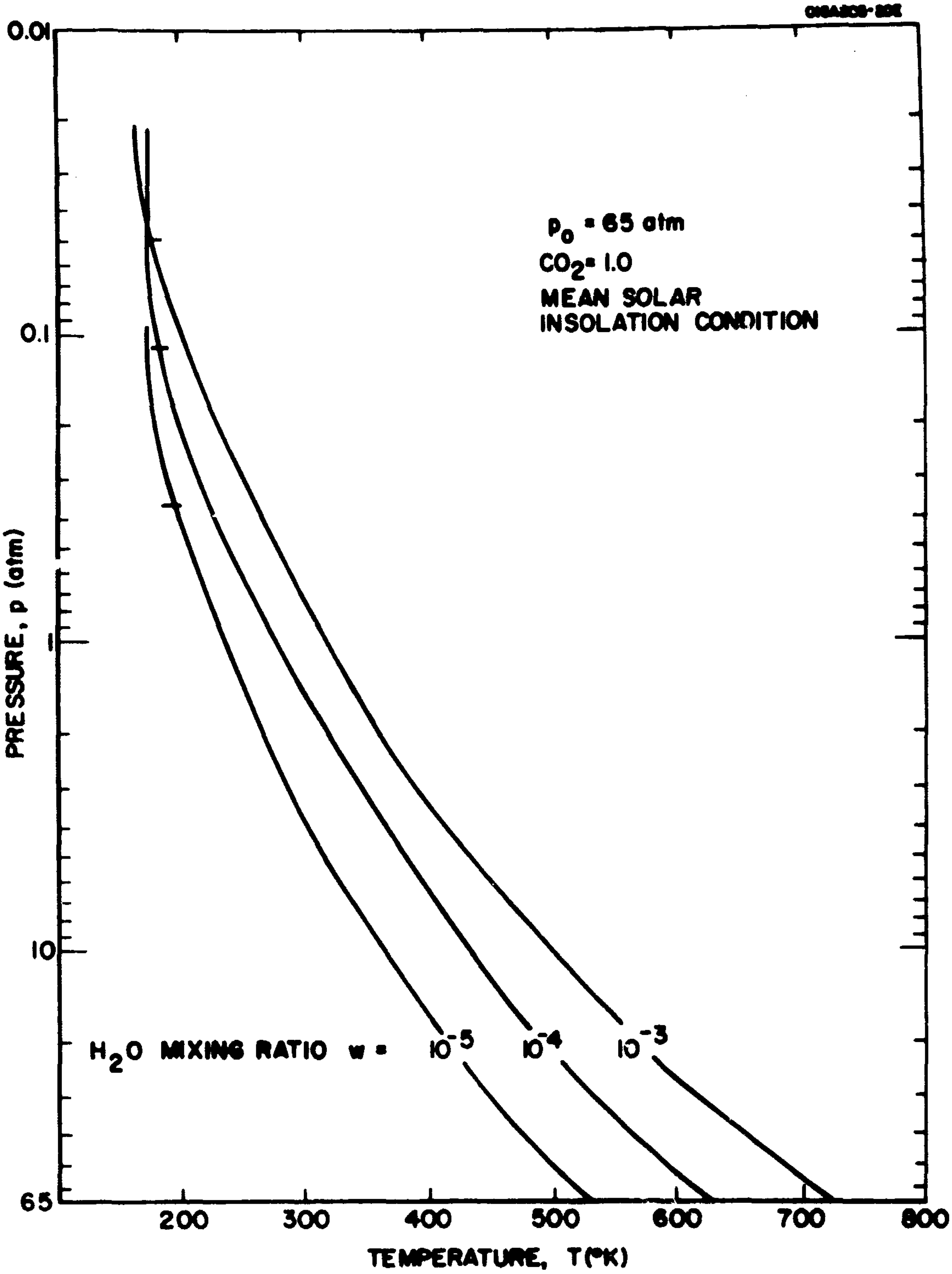

Figure 3. Thermal equilibrium temperature profiles for Venus for different water vapor mixing ratios. (Short horizontal dashes indicate computed tropopause height.)

(Jastrow, 1968). Venera 5 and 6 also did not reach the surface of Venus, but rather levels of ~ 80,000 ft and ~35,000 ft, respectively. Adiabatic extrapolation to the surface yields surface pressures of about 60 atm for Venera 6 and 140 atm for Venera 5 (Icarus, 1969; Avduevsky, et al., 1970). The large difference between the Venera 5 and 6 observations may be due to the possibility that Venera 6 may have been over a Venusian mountain at the time of its last radar-altimeter observation. Figure 4 shows the temperature profiles computed for the different surface pressures. The same model atmosphere as was used in the water vapor calculations is used here with an H_2O mixing ratio of 10^{-3}. The vertical coordinate in this diagram is the ratio of atmospheric pressure to surface pressure. These computations indicate that the surface temperature varies from 490°K to 775°K as the surface pressure is changed from 10 to 100 atm. The computations suggest that temperatures of 700°K or more require surface pressures $\geq$ 60 atm, with the assumed model atmosphere. The computed surface temperatures are in good agreement with those extrapolated for Venera 5 (830°K at p_o of 142 atm) and Venera 6 (710°K at p_o of 62 atm) (Avduesvky, et al., 1970). It is obvious from the diagram that the surface pressure originally reported for Venus - 20 atm - produces too small a greenhouse effect to permit the surface temperatures of ~ 700°K that are observed on Venus. It is interesting to note that an increase in surface pressure of 10 atm, from 10 to 20 atm, causes an increase in surface temperature of ~ 70°K, while an increase of surface pressure 3.5 times this amount (35 atm), from a surface pressure of 65 atm to 100 atm, causes an increase in surface temperature that is less than 70°K. Thus, despite the present uncertainty in surface pressure - according to Venera 5 and 6 the Venusian surface pressure may range from 60 to 140 atm - a good estimate of surface temperature can be calculated because of the relative insensitivity of surface temperature to surface pressure in this range of pressure. For further calculations of the temperature climate on Venus we adopt a surface pressure of 65 atm.

The carbon dioxide concentration in the Venusian atmosphere is also somewhat uncertain. The Mariner 5 radio occultation results suggest that the Venusian atmosphere is 75 to 90 percent carbon dioxide (Kliore et al., 1967); the Venera 4 results suggest $\geq$ 90 percent (Avduevksy et al., 1968); and Venera 5 and Venera 6 suggest 93 to 97 percent carbon dioxide (Avduevsky et al., 1970). Sagan and Pollack (1969) argue, on the basis of their analysis of the Mariner 5 and Venera 4 observations that the CO_2 mixing ratio lies between 50 and 85 percent. To examine the sensitivity of the temperature profile to carbon dioxide, a thermal equilibrium calculation was performed with a model atmosphere containing 50 percent CO_2. The computed temperature profile is very similar to the temperature profile computed for 100 percent CO_2, the temperatures being some 20°K lower. In both calculations, the model atmosphere discussed above was used. This calculation suggests that the Venusian temperature profile is in-

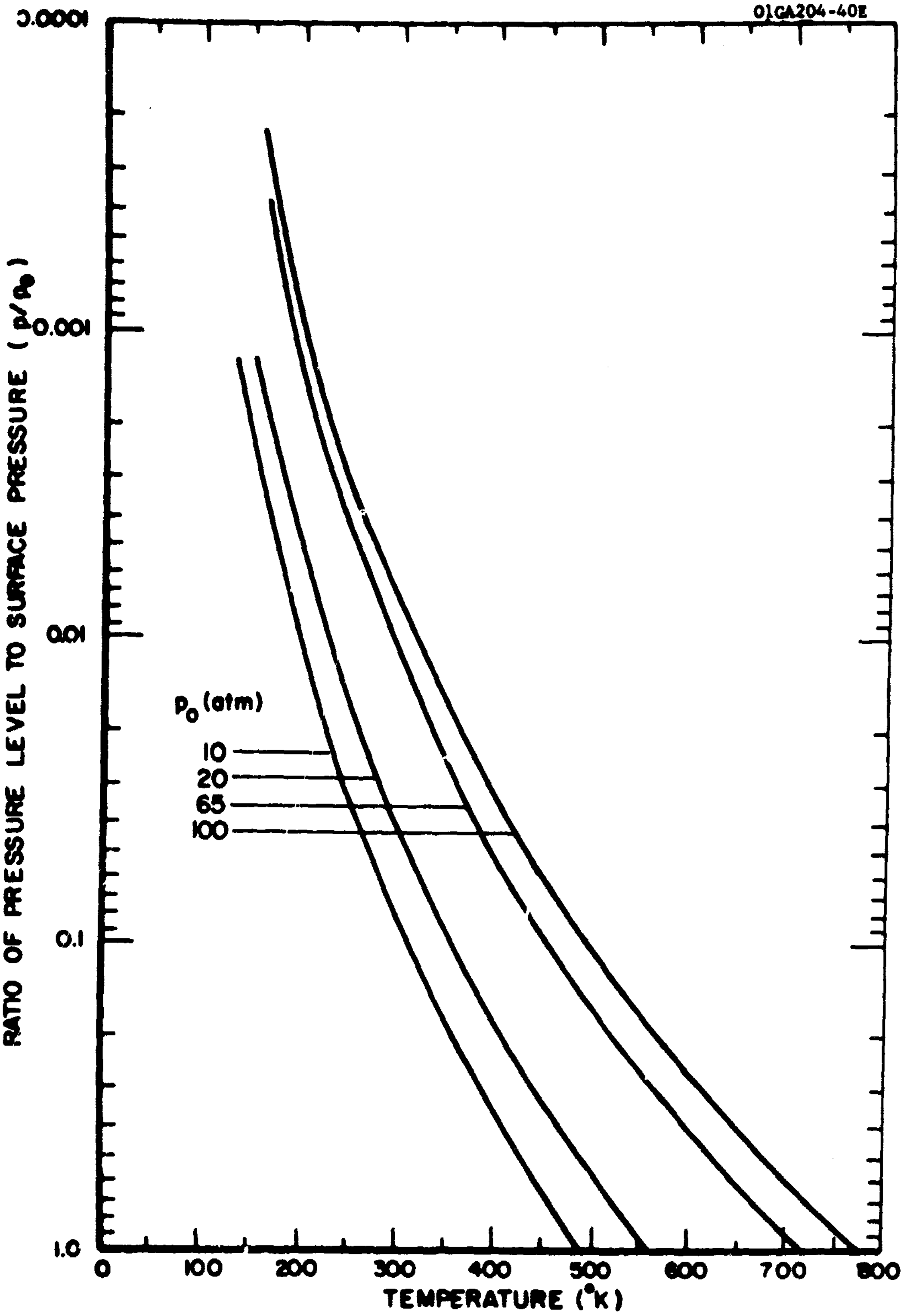

Figure 4. Computed thermal equilibrium temperature profiles for Venus for a range of assumed surface pressures, p_0.

sensitive to the exact carbon dioxide mixing ratio, if the carbon dioxide mixing ratio is greater than 0.50. For calculations of the temperature climate, a 100 percent CO_2 atmosphere is used.

On the basis of available observations and the calculations discussed above, a set of model atmosphere parameters was chosen for calculations of the latitudinal variation of the vertical temperature profile on Venus. These are listed in Table 1.

TABLE 1

MODEL ATMOSPHERE PARAMETERS FOR THERMAL EQUILIBRIUM CALCULATIONS OF VENUSIAN TEMPERATURE CLIMATE

Surface pressure	65 atm
CO_2 mixing ratio	1.0
H_2O mixing ratio	10^{-3}
Planetary albedo	0.73
Convective lapse-rate	$9^{\circ}C/km$

To determine the latitudinal variation of Venusian temperatures with the thermal equilibrium model, we must use the average solar input for each latitude. This is a function of the value of the cosine of the solar zenith angle averaged over a Venusian day. Observations indicate that the tilt of the Venusian axis of rotation is only a few degrees at most; therefore, to determine the average solar input, we assume that the tilt is zero degrees. With this assumption, the average value of the cosine of the solar zenith angle can be written

$$\overline{\cos \zeta} = \left[\frac{2 \int_0^{\pi/2} \cos \zeta \; dh}{\int_0^{\pi/2} dh} + 0 \right] \Big/ 2 \qquad (22)$$

where ζ is the zenith angle and h is the solar hour angle (which is equal to 0 at noon and $\pi/2$ at sunset). The first term in the brackets represents the average value of $\cos \zeta$ during the daytime and the second term the average value of $\cos \zeta$ at night.

In general, cos ζ for a planet can be written as

$$\cos \zeta = \sin \Phi \sin \delta + \cos \Phi \cos \delta \cos h \tag{23}$$

where Φ is latitude, and δ is the solar declination. Since the tilt or inclination of Venus is zero, δ is zero at all times. With $\delta = 0$, we have

$$\overline{\cos \zeta} = \left[\int_0^{\pi/2} \cos \Phi \cos h \, dh \right] / \pi \tag{24}$$

or

$$\overline{\cos \zeta} = (\cos \Phi)/\pi \tag{25}$$

Table 2 shows the latitudes for which we computed temperature profiles, the average values of cos ζ, and the values of ζ. Calculations of the temperature profile were performed at five latitudes - 0°, 20°, 40°, 60° and 80°. For these computations the model atmosphere and computational parameters listed in Table 1 were assumed.

TABLE 2

$\Phi(^\circ)$	$\cos \Phi$	$\overline{\cos \zeta}$	$\zeta(^\circ)$	ζ(Radians)
0	1.0	.32	71	1.24
20	.94	.30	73	1.27
40	.77	.245	76	1.33
60	.50	.159	81	1.41
80	.17	.0542	87	1.52

The results of the calculations are plotted in Figure 5 in the form of vertical temperature profiles. The computed surface temperature varies from 764°K at the equator to 477°K at 80° latitude. Well over half of the planet (up to 40+ degrees of latitude) has a surface temperature greater than 700°K.

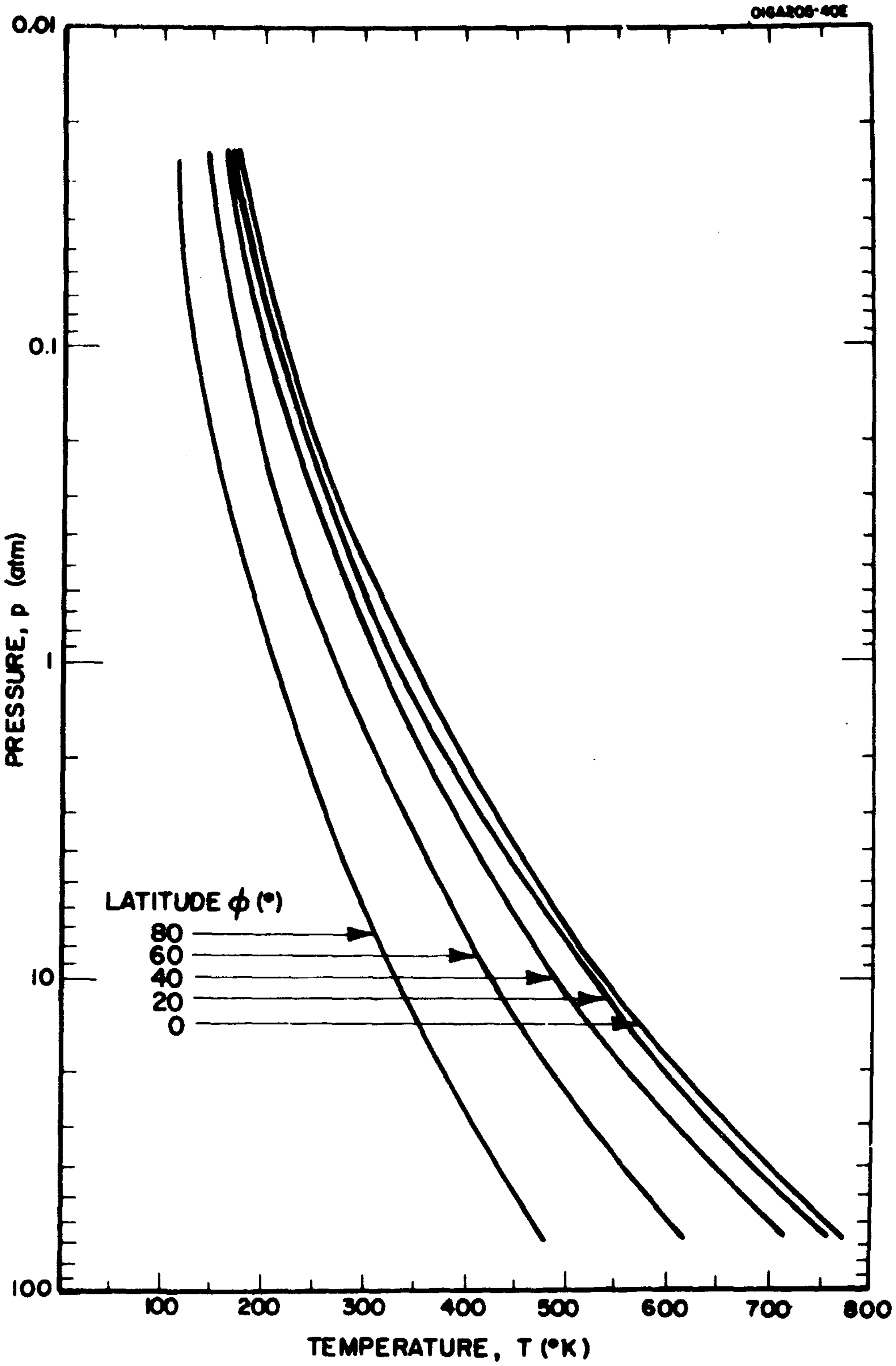

Figure 5. Thermal equilibrium temperature profiles for different latitudes on Venus.

The computed profiles are adiabatic up to a pressure level of about 0.1 atm. Thus the tropopause on Venus is located at a pressure level of the order of 10^{-3} of the surface pressure compared to 10^{-1} for the earth's tropopause. The latitudinal gradient of temperature between the equator and 80° varies from 287°K at the surface to only about 80°K at a pressure of 0.1 atm.

In Figure 6, we compare space probe temperature observations with our theoretical calculations. The space probe observations are based upon the Mariner 5 occultation experiment (Eshleman, 1970) and the Venera 4 (Mikhnevich and Sokolov, 1969) and Venera 5 and 6 (Avduevsky et al., 1970) direct temperature soundings. The space probe observations are all from the region 0 to 35° latitude and we have plotted the thermal equilibrium profile for 20° latitude for comparison with the observations. There are several interesting features of the observed profiles:
(1) Theoretically, the Venera temperatures, which were all made between 0 and 10° should be warmer than the Mariner temperatures which refer to 35° latitude. Actually, the Venera temperatures are equal to or colder than the Mariner temperatures; (2) Theoretically, one would expect the night temperatures to be less than the day temperatures. The Mariner 5 observations indicate that the nightside at 35°N is warmer than the day side at 35°S. Before attempting explanations of these two unusual features, we should have them verified by additional observations. Generally speaking, the agreement among the various observations, and the agreement of the observations with the theoretical calculations is good. The theoretical calculation yields temperatures lower than those observed in the upper part of the atmosphere. This is probably due to too much water vapor in the upper levels of the theoretical model, which would tend to cool this region by infrared emission.

The thermal equilibrium calculations are based upon mean solar insolation conditions for a diurnal cycle. If there are substantial diurnal temperature variations, the computed profiles would represent a mean daily temperature profile.

Early microwave observations indicated a large diurnal variation of surface temperature, and on the basis of such observations Pollack and Sagan (1965) suggested the following characteristics of the surface temperature climate of Venus: Average dark side temperature, ~ 600°K, average bright side, ~ 800°K, sub-solar point, ~ 1000°K, anti-solar point, ~ 610°K, and pole temperature of ~ 470°K. However, more recent microwave observations indicate that the diurnal effect is much smaller. In Table 3, after Kuzmin (1970), are tabulated differences in brightness temperatures between the day and night sides of Venus as observed at various microwave wavelengths. The observations at wavelengths of 10 cm or more refer to the surface while the observations at shorter wavelengths, are affected by the atmosphere. These observations indicate that the diurnal range of temperature in Venus is much smaller than originally believed and may, in fact, be negligible.

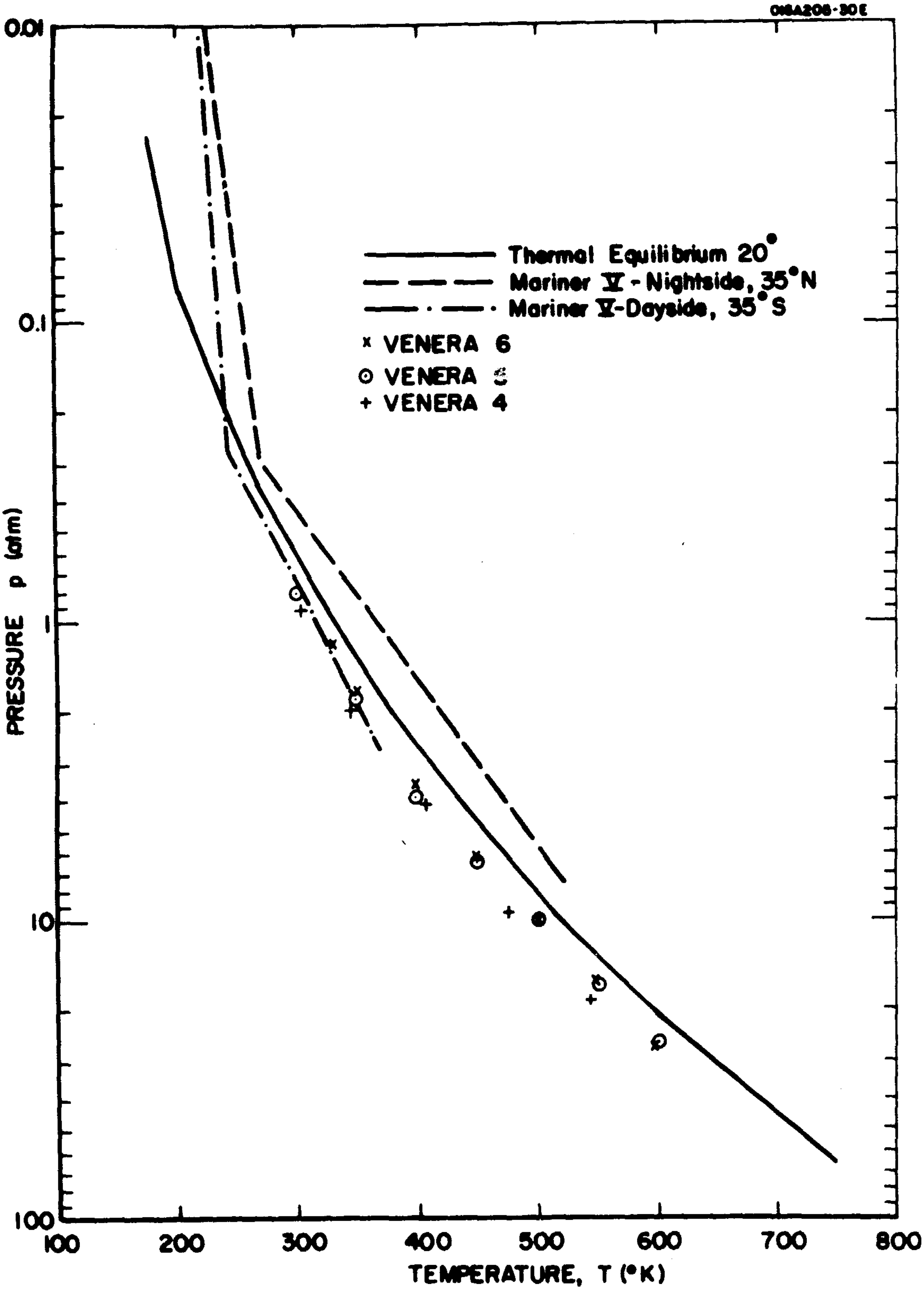

Figure 6. Comparison of spaceprobe observations of Venusian temperatures with thermal equilibrium calculation.

TABLE 3

DIFFERENCE OF BRIGHTNESS TEMPERATURE OF DAYSIDE (T_{BI}) AND NIGHTSIDE (T_{BU}) VENUS HEMISPHERES (AFTER KUZMIN, 1970)

	λ	$T_{BI} - T_{BU}$	Observers*
	(cm)	(°K)	
	.23	55 ± 60	Ephavov et al. (68)
	.34	-22 ± 4	Epstein et al. (68)
	.8	84 ± 70	Basharinov et al. (64)
	.8	120 ± 100	Ephanov et al. (68)
	.86	20 ± 8	Kalaghan et al. (68)
	1.95	0 ± 25	Morrison (69)
	3.75	74	Dickel (66)
	4.52	2 ± 20	Dickel et al. (68)
Originates mostly from sfc	10	26 ± 50	Drake (64)
	10.6	-30 ± 30	Kuzmin (66)
	11.3	24 + 50	Kellerman (66)

*Please refer to Kuzmin (1970) for complete bibliographic citations for observers.

The problem of the diurnal variation of Venusian temperature can be approached theoretically. As shown by Goody (1969), if all of the solar energy available for Venus is deposited in its atmosphere, an average increase of only 2°C would occur during a Venusian day (~ 120 Earth days). This value is comparable to that obtained for Earth, and suggests that diurnal variations of atmospheric temperature on Venus are small. Time dependent calculations of Venusian temperatures with a grey radiative-convective model (Gierasch and Goody, 1970) also yield small values for the diurnal temperature amplitude - 2.5°K at the surface, 0.5°K at 10 km, and 0.2°K at 38 km. However, steady state day and night profiles computed for the stratosphere (Bartko and Hanel, 1968) indicate diurnal ranges of 50 to 100°K at pressure levels between 10^{-2} and 10^{-3} mb.

Another theoretical approach to the problem of estimating the magnitude of diurnal effects on Venus is to compute the infrared cooling rate of the atmosphere for nighttime conditions - i.e., no sunlight. This cooling rate can then be used to obtain an order of magnitude estimate of the cooling of the atmosphere during the long Venusian night. We have performed such a calculation utilizing the model atmosphere of Table 1, and assuming a surface temperature of 700°K with adiabatic temperature decrease with altitude. This computation indicates that the Venusian atmosphere cools at an average rate of 1.7×10^{-2} °C per Earth day. Since the Venusian night is about 60 Earth-days long, this would mean an average decrease of 1°C during the long Venusian night. The computation also indicates a large variation of the cooling rate with altitude from values of the order 10^{-3} °C/Earth-day near the surface to ~ 1°C/Earth-day at pressure levels of tenths of an atmosphere. This suggests that temperatures in the lower atmosphere of Venus should not change diurnally, while temperatures in the upper atmosphere - pressure levels less than 1 atm - could undergo relatively large diurnal changes.

Thus, both the observational evidence and the theoretical evidence suggest that, for the surface and bulk of the Venus atmosphere, diurnal temperature variations are negligible. This, despite the relatively long days and nights and Venus. The reason for this behavior is the large heat capacity of such a thick atmosphere.

The energy balance associated with a thermal equilibrium temperature profile is depicted in Figure 7. This is for the case of mean solar insolation, surface pressure of 65 atm, water vapor mixing ratio of 10^{-3}, and 100 percent carbon dioxide. The solar energy impinging on the top of the atmosphere has been corrected for albedo losses. A major difference between this diagram and similar ones for Earth is in the ratio of the downward infrared flux to the solar flux at the surface. On Earth, this ratio is about 2, on Venus it is about 100. The difference is a manifestation of the enormous greenhouse effect on Venus. One can also compare the ratios of convective heat flux to the solar flux at

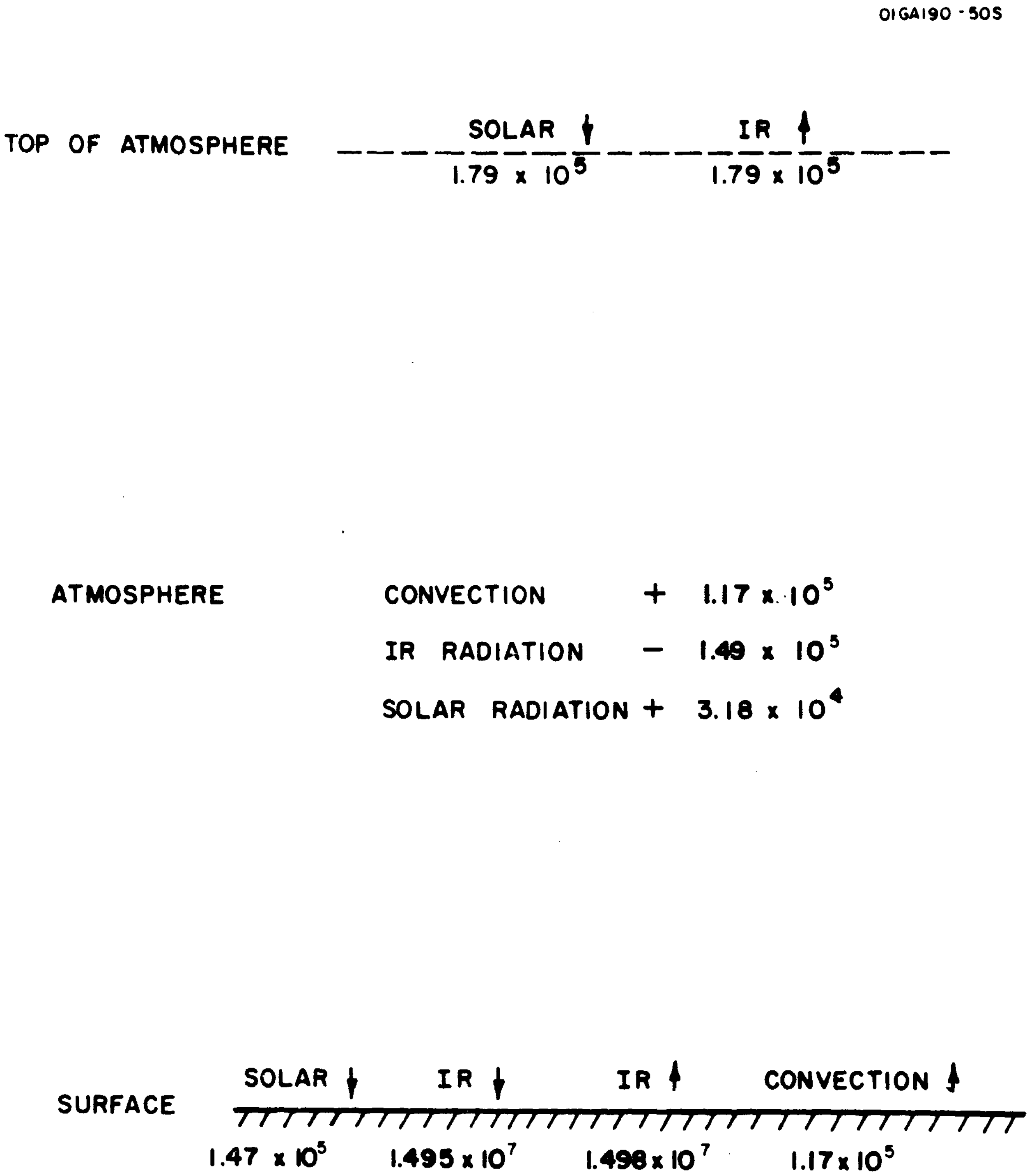

Figure 7. Energy balance diagram for thermal equilbrium temperature profile for H_2O mixing ratio of 10^{-3} (energy units are ergs cm^{-2} sec^{-1}).

the surface for the two planets. For Venus, we have about 0.8; for Earth - if we include both latent and sensible heat as the convective heat flux - we have about 0.62. Thus, these ratios are similar, suggesting that convective processes have equal importance on the two planets.

The thermal equilibrium concept is one of local equilibrium. That is, at each latitude the temperature profile depends upon the input of solar energy appropriate for that latitude. Thus, the effects of circulation processes on the temperature profile are not included. To include the effects of circulation one would have to model the entire general circulation of the Venusian atmosphere - a complex task that is beyond the scope of this paper. However, we can estimate qualitatively the direction that the effects of the circulation would take. The equator to pole temperature decrease produced by solar heating of Venus would cause a poleward directed pressure decrease at upper levels. This would initiate a circulation toward the pole at upper levels, toward the equator at lower levels. Because of the slow rotation rate of the planet this circulation - a Hadley cell - might be the prevailing one. The net effect of this circulation would be a transfer of heat energy poleward, thus reducing temperatures in equatorial regions and raising them in polar regions. According to our thermal equilibrium calculations, the latitudinal temperature difference at upper levels is already small - about 80°K between equator and 80° latitude at $p = 0.1$ atm -so that the circulation could not cause too great a change at these levels. At the surface, the temperature difference between equator and 80° latitude is about 285°K, and the circulation could cause a substantial change in the thermal equilibrium temperatures. However, the comparison between our computed thermal equilibrium temperature profile for 20° latitude with the space probe observations for the same latitude zone shows good agreement. This suggests that the effects of the circulation on the thermal equilibrium temperatures may not be large. If this is so, our thermal equilibrium temperatures provide a good first estimate of the temperature climate of Venus.

Based upon the thermal equilibrium calculations,we have prepared,in Figure 8, a vertical cross-section through the atmosphere of Venus extending from the equator to 80° latitude and from the surface to 0.02 atm pressure. Shown on the cross-section are isopleths of temperature drawn on the basis of the thermal equilibrium temperature profiles at the five latitudes 0°, 20°, 40°, 60° and 80°. This cross-section permits estimation of temperature on Venus for any latitude and height within the range covered. As discussed above, the correction to these thermal equilibrium temperatures is probably small at the lower latitudes. However, at high latitudes - for example, at 90°, where thermal equilibrium would yield $T = 0$ because solar insolation equals zero - large positive corrections may be applicable. Also, comparison of the theoretical profiles with the space probe observations suggests that the upper level temperatures are probably too low by perhaps 50°K. Aside from these reservations, the cross-section provides a first estimate of the temperature climate of Venus.

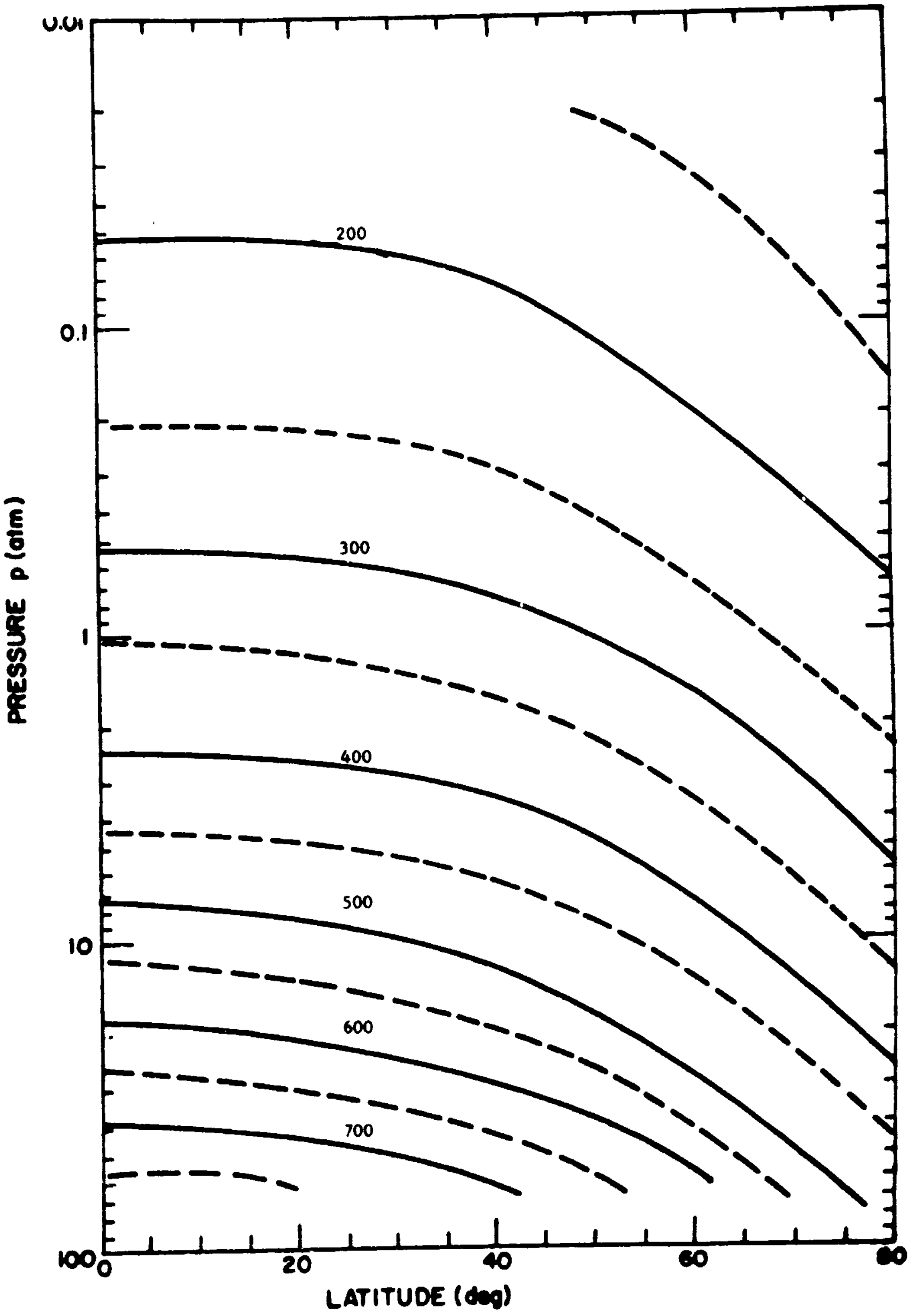

Figure 8. Temperature cross-section through the atmosphere of Venus extending from the equator to 80° latitude. Isotherms are based upon thermal equilibrium calculations and are labelled in degrees Kelvin.

E. Discussion and Conclusions

The non-grey thermal equilibrium calculations reported here implicitly assume that, aside from causing a high planetary albedo, the effect of the Venusian cloud on the temperature profile is negligible. The close correspondence between the observed Venusian temperatures and the theoretically computed temperatures indicates that this may not be too bad an assumption. Several theoretical studies have dealt specifically with the effect of the cloud layer. Samuelson (1968) has computed radiative equilibrium temperature profiles for a pure particulate medium that is intended to represent the clouds of Venus. He finds a mean surface temperature of 480°K and suggestions of an isothermal region near the surface. His computed surface temperature is lower than that observed for Venus. Gierash and Goody (1970) have recently performed radiative-convective equilibrium calculations with a "semi-grey" - two different absorption coefficients for solar and thermal radiation - model that includes cloud and gas radiative effects and the iteraction between cloud formation and the temperature field. They find that no type of cloud, dust or condensible vapor, is fully satisfactory (i.e., satisfies certain observational constraints). They conclude that the Venus clouds are not in a local radiative-convective state, and that it is plausible that the temperatures of the interior of the cloud are controlled by heat transfer due to the large scale planetary circulation.

The major uncertainty in our calculations is the infrared transmittance of carbon dioxide and water vapor at the high pressures and path lengths of the atmosphere of Venus. Experimental values of transmittance for such high pressures and path lengths are not currently available, and extrapolations - even if based upon theoretical reasoning - may be in error.

As stated above, good agreement is obtained between observed and computed thermal equilibrium temperatures. However, this is only for a model atmosphere with a water vapor mixing ratio of order of 10^{-3}, as measured by the Venera spacecraft. If actual water vapor mixing ratios are lower, as implied by the Earth-based spectrographic observations, the computed temperatures would be lower than those observed. Furthermore, since there are no observations of temperatures in the lower atmosphere of Venus - i.e., at pressures greater than 26 atm - the lower portions of the computed temperature profiles have not been verified - except in the sense that the computed surface temperature of $\sim$ 700°K is in agreement with the surface temperature derived from the microwave observations. An analysis of recent interferometric observations of Venus at 11.1 cm (Sinclair et al., 1970) suggests an isothermal lower atmosphere. Furthermore, this same study suggests that the polar temperatures on Venus do not differ significantly from the equatorial temperatures - < 12°K. Both of these findings appear to be in contradiction to the results of the present calculations.

We may conclude that the present thermal equilibrium temperature calculations, which are based upon a model atmospheric composition and

and pressure that is reasonably compatible with current knowledge, yields temperature profiles in good agreement with the spaceprobe temperature observations of Mariner 5, and Veneras 4, 5, and 6. The latitudinal temperature cross-section constructed from these calculations may be used, with due caution, as a first estimate of the temperature climate of Venus.

SECTION IV

ARE THE CLOUDS OF VENUS COMPOSED OF H_2O?

A. Background

The question of the composition of the clouds of Venus is still quite open. For a long time, when astronomers looked at Venus through their telescopes and saw the bright white disk they thought they were viewing water clouds, similar to terrestrial clouds, in the Venusian atmosphere. Earth based spectroscopic observations have indeed found water vapor in the Venusian atmosphere, but in small amounts (see, for example, Belton, 1968). Depending upon what one assumes about the variation of the water vapor mixing ratio with altitude, and the temperatures in the vicinity of the clouds, one can marginally show that some of the spectroscopically observed water vapor amounts are compatible with H_2O ice crystal clouds (Ohring,1966). Bottema, et al, (1964), on the basis of an analysis of the near infrared reflection spectrum of Venus, obtained from a high altitude baloon flight, concluded that the Venusian clouds were composed of ice crystals. These observations were also analyzed by Sagan and Pollack (1967) and Pollack and Sagan (1968), who agree with the ice crystal interpretation, and Rea and O'Leary (1968), who conclude that the clouds are "almost certainly not composed of H_2O ice". Arking and Potter (1968) find good agreement between observed and calculated phase curves in the U, B, and V spectral regions, if a terrestrial type cloud consisting of spherical water droplets or ice particles with radii around 4μ is assumed. The Venera 4 observations indicate water vapor concentrations of 0.1 to 0.7% by volume (Vinogradov et al, 1968) – two to three orders of magnitude higher than those deduced spectroscopically. This discrepancy may be explained by the difference in altitudes of the measurements – the spectroscopic observations referring to the upper atmosphere, the Venera 4 observations to the lower atmosphere.

Thus, at the present time, there is much diverse and conflicting information available concerning the hypothesis that the clouds of Venus are composed of H_2O. In this paper we review and analyze this information from a meteorological point of view in order to evaluate the validity of the hypothesis. Our approach is outlined below.

B. Approach

From a meteorological point of view, an assessment of the hypothesis that the Venusian clouds are H_2O clouds is quite simple. One has only to compare the actual water vapor concentration in an atmospheric layer with the water vapor concentration required for saturation. If the atmospheric layer is saturated, then any clouds in the layer are water or ice clouds. If the atmospheric layer is not saturated, then any clouds in the layer are not composed of H_2O. The obstacle to this simple assessment scheme is the uncertainty in the two quantities required for the evaluation – the actual water vapor concentration and the saturation water vapor concentration.

The available evidence concerning actual water vapor concentrations in the atmosphere of Venus consists mainly of Earth-based spectroscopic observations, Venera 4, 5, and 6 direct sampling observations, and inferences based upon microwave observations. There are difficulties associated with each of these observational techniques. However, we shall utilize them for our estimates of actual water vapor concentrations.

The actual water vapor concentrations are to be compared to the concentrations required for saturation. The saturation vapor pressure of water vapor is a function of temperature only. Thus, if we have estimates of the vertical profile of temperature (temperature versus pressure) we can determine the saturation vapor pressures and saturation mixing ratios. For our estimates of temperature profiles, we shall rely on our theoretical thermal equilibrium calculations (Section 3) and on the observations of Mariner 5 and Veneras 4, 5, and 6.

C. Analysis

The spectroscopic observations of water vapor in the Venusian atmosphere are extremely difficult to interpret, since the signal arises from a scattering layer of unknown thickness. When analyzed, these observations provide information on an integrated amount of water vapor along some atmospheric path. Much of this path may be within the cloud layer – the result of many scattering processes. The observations generally are reduced to yield an abundance of H_2O in a vertical column through the atmosphere of Venus "above the clouds". But, as indicated above, the observed abundance may not actually represent the abundance above the clouds; and, even if it does, the pressure level of the clouds must be known if one wants to estimate the observed water vapor mixing ratio, which is the quantity that is needed to determine if the atmosphere is saturated with respect to water vapor. Schorn et al (1969) have summarized recent spectroscopic estimates of Venusian H_2O abundance; these are listed in Table 4. In this table, i is the phase angle, the planetocentric angle between the sun and the Earth, and "shift" is the direction of the Doppler shift at the time of the observations. In terms of water vapor mixing ratio, Belton (1968) finds a value of 10^{-4} at a pressure level of about 0.2 atm for the Belton and Hunten (1966) observations; Kuiper (1968) finds a mixing ratio of $\sim 10^{-6}$.

Direct observations of the Venusian water vapor concentrations have been performed by the Venera 4 (Vinogradov et al., 1968) and Venera 5 and 6 (Avduevsky et al., 1970) spacecraft. The Venera 4 observations indicate an H_2O volume percentage of greater than 0.1% at the 0.73 atm level, and between 0.05 and 0.7% at the 2 atm level. The water vapor mixing ratio represents a mass fraction rather than a volumetric fraction, since it is defined as

$$w = \rho_{H_2O}/\rho$$

where w is the mixing ratio, H_2O the density of the water vapor, and ρ the density of the atmosphere. Hence the mixing ratios corresponding to the above volumetric percentages are 4×10^{-4}, 2×10^{-4}, and 3×10^{-3}. The Venera 5 and 6 observations indicate on H_2O vapor content of between 4 and 11 mg liter^{-1} at a pressure level of 0.6 atm. This corresponds to a

TABLE 4

ESTIMATES OF H_2O ABUNDANCE IN A VERTICAL COLUMN "ABOVE THE CLOUDS" OF VENUS (SHORN ET AL, 1969)

Date	i	Shift	Band(s) (μ)	Amount(μ)	Observers *
Jan. 21-22,1963	-	--	1.38	70	Dollfus (1965)
Feb. 21,1964	65	Blue	1.13	52-222	Strong (1965)
April 28, 1963	101	Blue	0.82	60	Spinrad and Shawl(1
April 29, 1964	102	Blue	0.82	60	Spinrad and Shawl(1
Nov. 17, 1964	51	Red	0.82	60	Spinrad and Shawl(1
Nov., 1965	~90	Blue	0.82	<125	Belton and Hunten(1
May, 1966	~70	Red	0.82	<125	Belton and Hunten(1
June-July,1966	60-40	Red	$1 < \lambda < 2$	<20	Connes et al, (1967
April, 1967	~55	Blue	0.82	<16	Owen (1967)
May 24, 1967	75	Blue	1.4, 1.9	~0	Kuiper (1968)
June 11,1967	85	Blue	1.4, 1.9	~0	Kuiper (1968)
April-June,1967	52-92	Blue	0.82	<32, <16	This paper
Nov.-Dec.,1967	87-68	Red	0.82	30-40	This paper
Nov., 1967	~80	Red	1.9,2.7	~2	Kuiper (1968)

Complete bibliographic citations for observers may be found in Shorn et al,1969.

water vapor mixing ratio of between 4 x 10^{-3} and 10^{-2}, assuming a temperature of 300°K at the point of observation and a pure CO_2 atmosphere. The mixing ratios observed by the Venera spacecraft are summarized in Table 5.

TABLE 5

A WATER VAPOR MIXING RATIOS (w) OBSERVED BY VENERA SPACECRAFT

Pressure (atm)	w
2	2 x 10^{-4} to 3 x 10^{-3}
0.73	$> 4 \times 10^{-4}$
0.60	4 x 10^{-3} to 10^{-2}

The mixing ratios observed by the Soviet spacecraft are as much as 10^4 greater than the lowest values observed spectroscopically. Lewis (1970) has suggested that there may be a large error in the spacecraft observed water vapor concentrations due to the presence of HCl in the atmosphere. The dissolved HCl may have enhanced conductivity of the electrical conductivity device used to detect the water vapor. Another possible reason for the general discrepancy between the spectroscopic observations and the spacecraft measurements is the difference in height levels to which the observations refer. The spectroscopic observations refer to higher levels in the atmosphere where water vapor mixing ratios may be lower.

Observed microwave spectra have been used by Pollack and Wood (1968) to set limits on the amount of water vapor in the atmosphere. They computed microwave brightness temperatures for a model atmosphere based upon the Venera 4 and Mariner 5 observations. By varying the assumed water vapor mixing ratios, and comparing the computed with the observed microwave spectra, they arrived at an upper limit of 8 x 10^{-3} for the Venusian water vapor mixing ratios. The observations did not permit setting a lower bound other than zero.

The saturation mixing ratios depend upon temperature. And since temperature varies with height and with latitude, so will the saturation mixing ratios. To compute the saturation mixing ratios we use the temperature profiles computed at the different latitudes with the thermal equilibrium model. We also use the temperature profiles observed by Mariner 5, and Veneras 4,5, and 6.

The analyses are presented in a series of similar graphs, Figures 9 through 13. On each graph is shown a temperature profile, lines of constant saturation mixing ratios (almost vertical lines) for the potential region of cloud formation, and integrated water vapor amounts above a series of levels in the atmosphere (numbers printed above horizontal lines). Integrated water vapor amounts as well as saturation mixing ratios are shown to facilitate comparison with both spectroscopic and spacecraft H_2O observationa. The integrated water vapor amounts are computed with the assumption that the atmosphere is saturated up to the level of the last mixing ratio shown, above which the mixing ratio is constant with altitude. Hence, for a given temperature profile, the computed integrated water vapor amounts are the maximum values that could be observed. Figures 9, 10, 11, and 12 are based upon the thermal equilibrium temperature profiles for 0°, 40°, 60°, and 80° latitude, respectively. Figure 13 is somewhat more complicated and includes an analysis for the thermal equilibrium temperature profile for 20° latitude as well as for temperatures observed by Mariner 5 and the Venera spacecraft.

Based upon infrared window radiation observations, the temperature in the vicinity of the cloud tops appears to be in the range 210°K to 240°K (see, for example, discussion in Ohring, 1966). Based upon an analysis of spectroscopic observations of Venus, Belton (1968) finds temperatures of 240°K to 270°K in the vicinity of the clouds. Thus, the observational evidence indicates that temperatures in the vicinity of the cloud tops are in the range 210°K to 270°K. Pressures in the vicinity of the clouds have been estimated at ~0.2 atm, with an uncertainty of a factor of two (Belton, 1968). In comparing observed water vapor amounts with those required for saturation, we shall concentrate on the part of the temperature profile between 210°K and 270°K, and the part of the pressure distribution between 0.1 and 0.4 atm. The section of the temperature profile between 210°K and 270°K is indicated by a heavier (thicker) line.

Let us examine Figure 9, which represents a temperature profile at the Venusian equator. The Venera observations, which indicate mixing ratios between $\sim 10^{-4}$ and $\sim 10^{-2}$ at pressure levels greater than 0.6 atm, are compatible with clouds in the 210°K to 270°K temperature range if these mixing ratios prevail at pressures lower than 0.6 atm. This figure also shows that if the cloud temperature is about 245°K, the spectroscopic water vapor observations should indicate about $3.3 \times 10^{2} \mu$ of integrated water vapor amount. But if the cloud temperature is about 220°K, the integrated water vapor amount above the clouds is only 17μ. Thus, even integrated water vapor amounts as low as $\sim 10\mu$ could be compatible with ice clouds, if the cloud temperatures are at the low end (210 K to 220°K) of the indicated range, if the temperature structure above the clouds is as shown in Figure 9, and if the cloud-top pressure is $\sim$ 0.1 atm.

Figure 10, representing a thermal equilibrium profile for 40° latitude, can be analyzed in a similar fashion. If the upper limit of the Venera 5 and 6 observed mixing ratio, $w = 10^{-2}$ at $p = 0.6$ atm, is correct, then the

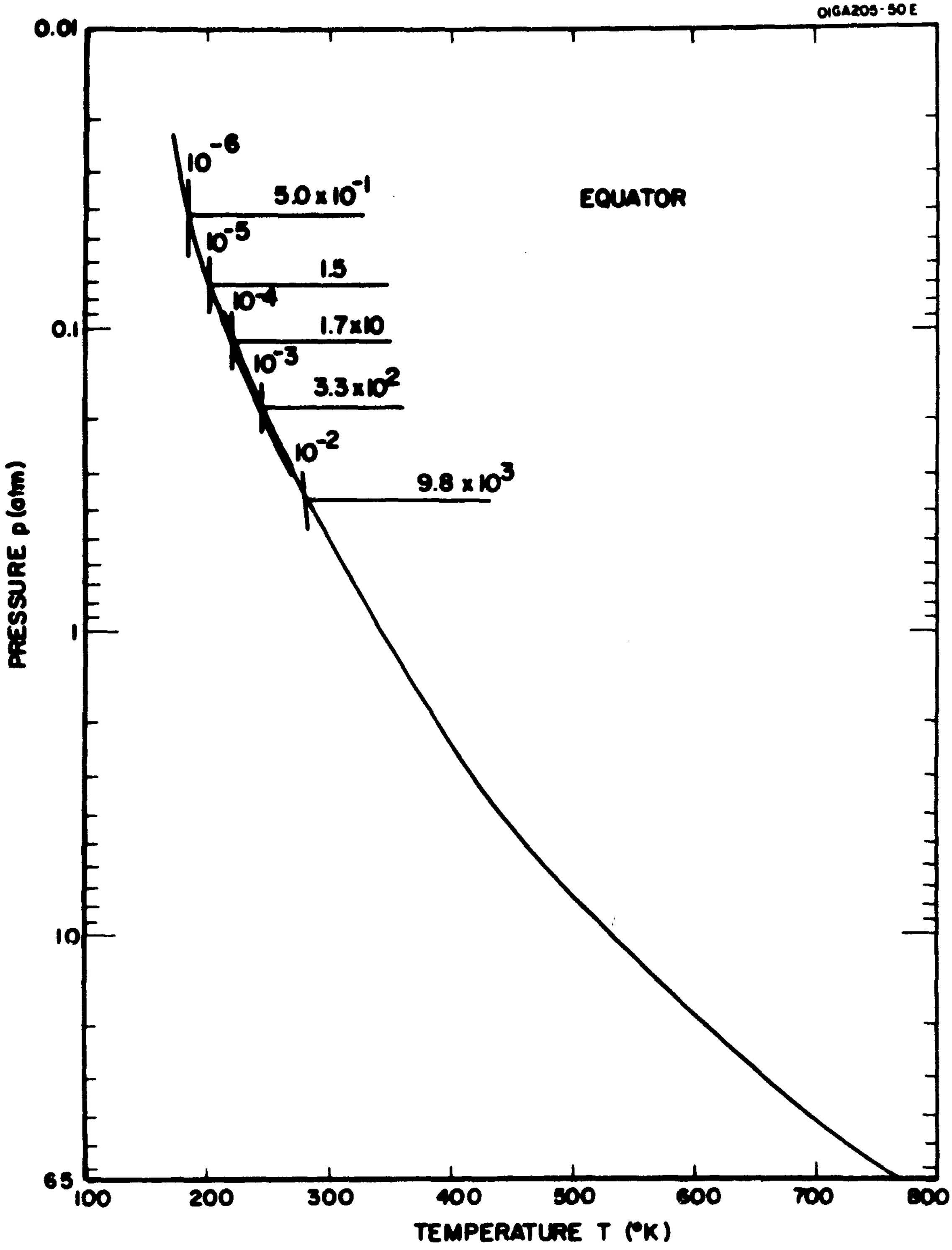

Figure 9. Thermal equilibrium temperature profile, saturation water vapor mixing ratios (labelled vertical lines), and integrated water vapor amounts above selected levels (numbers above horizontal lines with units of microns (μ) of precipitable water) for Venusian equator. The 210°K to 270°K region of the temperature profile is emphasized by a thicker line.

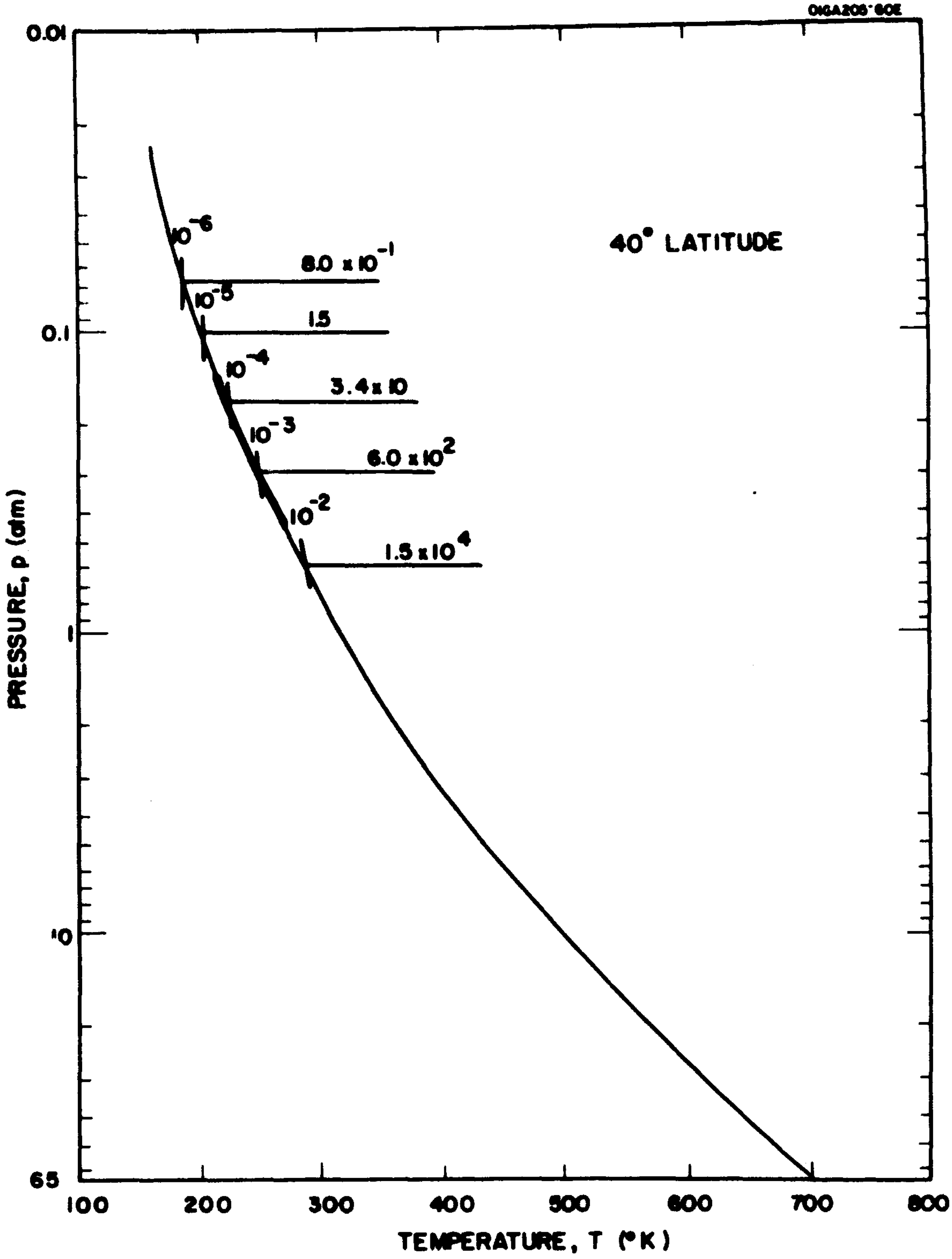

Figure 10. Thermal equilibrium temperature profile, saturation water vapor mixing ratios (labelled vertical lines), and integrated water vapor amounts above selected levels (numbers above horizontal lines with units of microns (μ) of precipitable water) for 40° latitude on Venus. The 210°K to 270°K region of the temperature profile is emphasized by a thicker line.

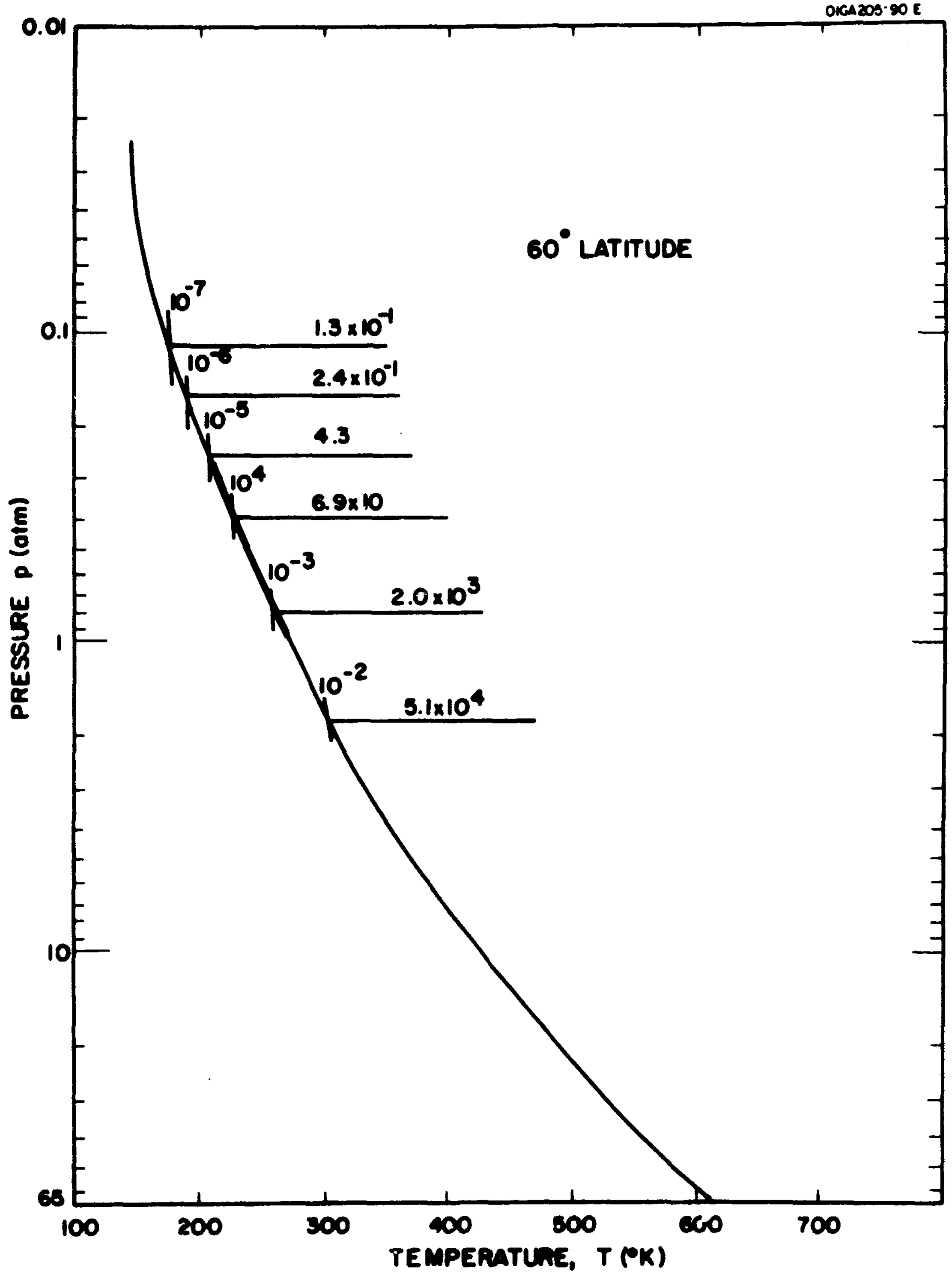

Figure 11. Thermal equilibrium temperature profile, saturation water vapor mixing ratios (labelled vertical lines), and integrated water vapor amounts above selected levels (numbers above horizontal lines with units of microns (μ) of precipitable water) for 60° latitude on Venus. The 210°K to 270°K region of the temperature profile is emphasized by a thicker line.

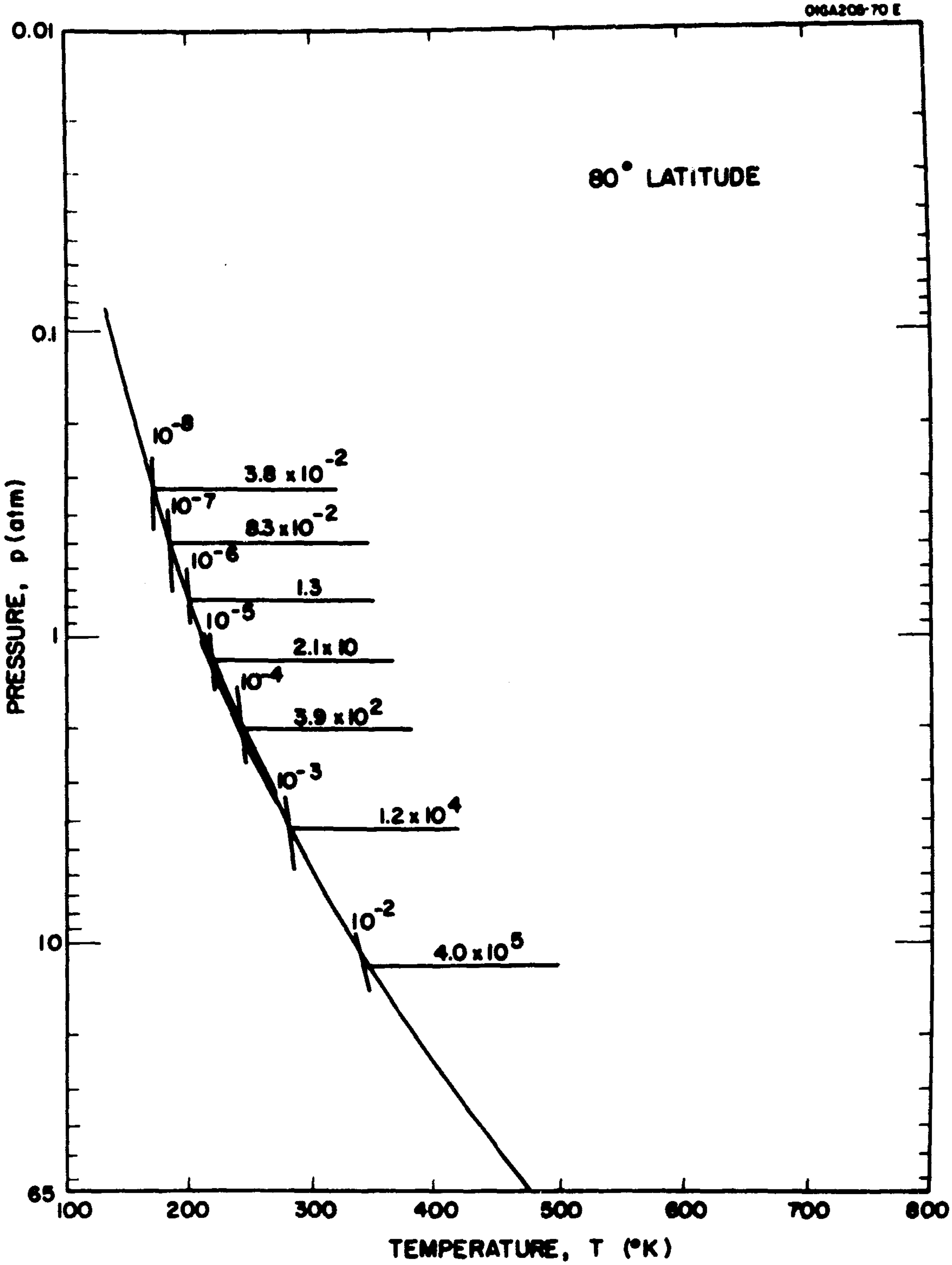

Figure 12. Thermal equilibrium temperature profile, saturation water vapor mixing ratios (labelled vertical lines), and integrated water vapor amounts above selected levels (numbers above horizontal lines with units of microns (μ) of precipitable water) for 80° latitude on Venus. The 210°K to 270°K region of the temperature profile is emphasized by a thicker line.

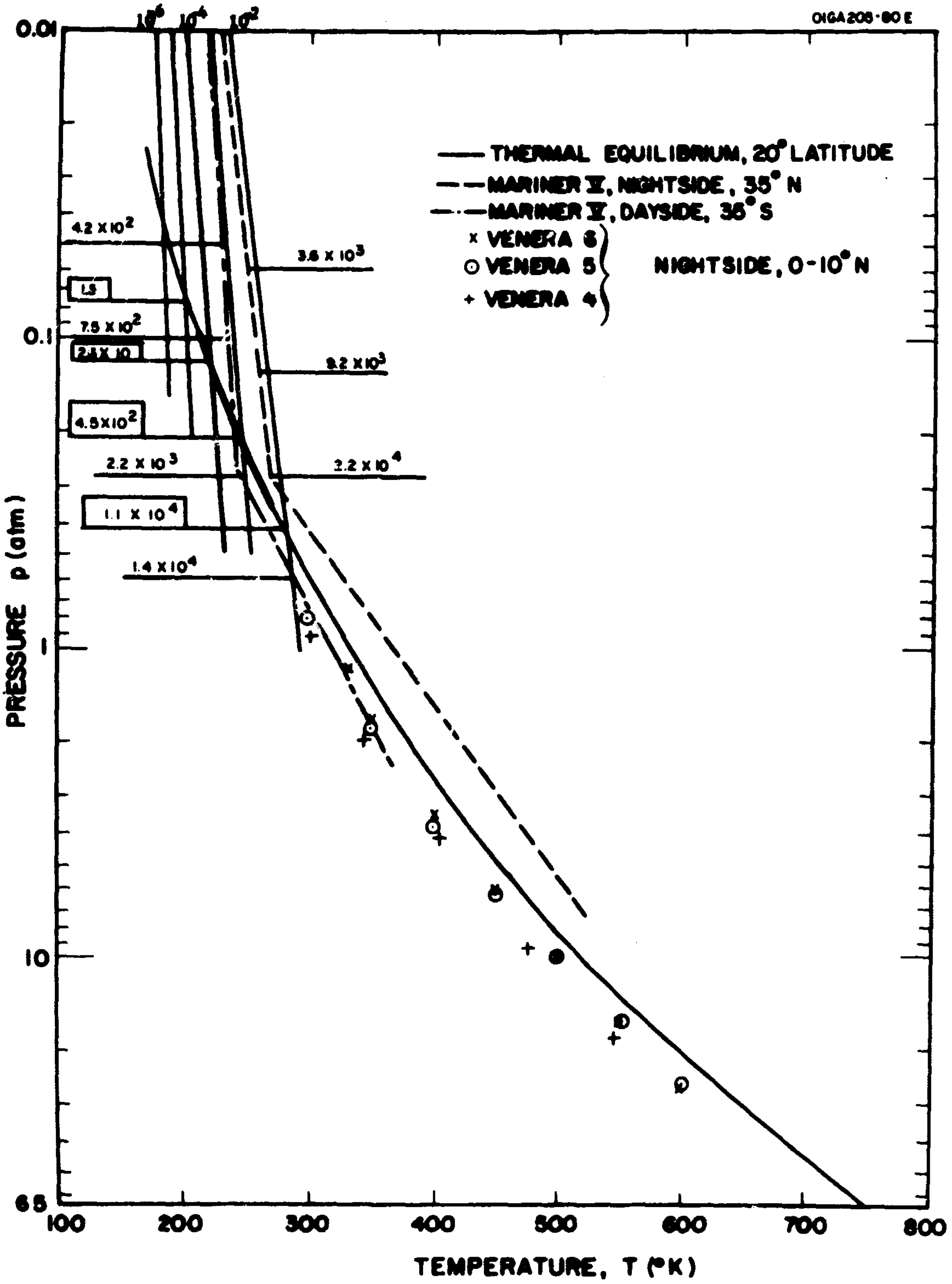

Figure 13. Thermal equilibrium temperature profile for 20° latitude, Mariner 5 dayside and nightside temperature profiles, Venera 4, 5, and 6 temperatures, saturation water vapor mixing ratios (labelled vertical lines), and integrated water vapor amounts above selected levels (numbers above horizontal lines with units of microns (μ) of precipitable water). Integrated H_2O amounts for Mariner 5 nightside are to right of temperature profiles; for Mariner 5 dayside to left of temperature profiles; and for thermal equilibrium to left of temperature profile and boxed in.

base of the cloud would form at p = 0.6 atm; if the lower limit of 4×10^{-3} is correct, the cloud base would form somewhere between 0.6 and 0.3 atm. Once again low spectroscopic amounts, ~10μ, are compatible with ice clouds, if cloud-top temperatures are 210°K to 220°K, cloud-top pressures are ~0.1 atm, and the temperature profile above the clouds is as shown in Figure 10.

Figures 11 and 12, representing thermal equilibrium profiles for 60° and 80° latitude, indicate that at the higher latitudes the 210°K to 270°K temperature region occurs at higher pressures. For example, at 80° latitude the 210°K to 270°K region lies in the pressure range 1 to 3.5 atm. This pressure range is outside of the pressure range suggested for the cloud tops by observations. Thus, although the spectroscopic water vapor observations may be in agreement with required saturation values for the 210°K to 270°K cloud-top temperature requirement, the pressures at which the cloud top would occur are outside of the "observed" cloud top pressure range.

The best current estimate of actual temperature profiles on Venus are those obtained from the Mariner 5 (Eshleman, 1970), Venera 4 (Mikhnevich and Sokolov, 1969), and Venera 5 and 6 (Avduevsky et al, 1970). These observed temperatures and a thermal equilibrium temperature profile for 20° latitude are shown in Figure 13. The warmest of these temperature profiles is the Mariner 5 nightside profile. In the temperature and pressure range of interest, i.e., 210°K to 270°K , 0.1 atm to 0.4 atm, mixing ratios of $\sim 6 \times 10^{-3}$ are required for saturation. These are compatible with the Venera observations but not with the spectroscopic observations. The maximum integrated water vapor amounts that could be observed with this temperature profile are high – 2.2×10^{4}μ above p = 0.28 atm, 3.6×10^{3}μ above p = 0.06 atm. There are several orders of magnitude greater than those observed spectroscopically. The Mariner 5 dayside profile, which appears to be in better agreement with the Venera temperatures, requires a mixing ratio of $\sim 10^{-3}$ for saturation in the region of interest. This is compatible with the Venera water vapor observations. The integrated water vapor amounts associated with this temperature profile are still high, e.g., 7.5×10^{2}μ above 0.1 atm, much higher than observed spectroscopically. Thus, on first analyses the spectroscopic water vapor amounts are incompatible with ice saturation for this temperature profile. However, if the temperatures in this region were slightly lower, spectroscopically observed integrated water vapor amounts would be compatible with those required for saturation. For example, if the temperature profile above the 0.2 atm level followed the thermal equilibrium profile, the temperature at the 0.1 atm level would be only about 20°K less than observed by Mariner 5 on the dayside. But the integrated water vapor amount required for saturation at this level drops from 7.5×10^{2}μ to <26μ, which would be compatible with some of the spectroscopic observations. Or, if the true temperature profile is similar to the Mariner 5 dayside profile, compatibility could also be achieved with the spectroscopic H_2O observations if the water vapor mixing ratio decreased more rapidly with height. For example, if the water vapor mixing ratio decreased above the 0.2 atm level at the same rate at which it decreases for the thermal equilibrium profile, compatibility would be achieved.

D. Summary and Conclusions

An attempt is made to answer the question, "Are the Clouds of Venus Composed of H_2O?" using a meteorological approach. The approach consists of comparing estimates of the actual water vapor amounts in the Venus atmosphere with those required for saturation. Estimates of actual water vapor amounts are obtained from the Venera spacecraft observations, which yield water vapor mixing ratios at certain levels in the atmosphere, and from the spectroscopic observations, which yield integrated water vapor amounts above the "clouds". Estimates of the water vapor amounts required for saturation are obtained from saturation mixing ratios computed for thermal equilibrium temperature profiles and for the temperature profiles observed by Mariner 5 and the Venera series of spacecraft. These can be compared directly with the observed mixing ratios. To estimate integrated water vapor amounts that are required for saturation – to compare with the spectroscopic observations of actual integrated water vapor amounts – requires some assumption for the distribution of water vapor mixing ratio above the level of saturation. In the present paper, it is assumed that the atmosphere is saturated at all levels above the level of interest. For a given temperature profile, this assumption leads to a maximum estimate of integrated water vapor amount required for saturation.

The analyses indicate that the water vapor mixing ratios observed by the Venera spacecraft are compatible with ice clouds occuring in the Venusian atmosphere at temperatures and pressures suggested by observations. The analyses also indicate that the spectroscopically determined water vapor amounts are not compatible with ice clouds if the actual temperature profile is similar to that observed by Mariner 5, but are compatible with ice clouds if the actual temperature profile is similar to the thermal equilibrium temperature profiles – which indicate temperatures at upper levels somewhat lower than observed. The spectroscopically observed water vapor amounts would also be compatible with ice clouds if the water vapor mixing ratio decreased above the cloud top at a rapid rate.

In conclusion, the present answer to the question, "Are the Clouds of Venus Composed of H_2O?" is "The evidence is not conclusive one way or another." To reach a more definitive answer with this meteorological approach, we would need more information, especially on how the water vapor mixing ratio actually varies with height above the clouds.

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