On the Temperature of the Jovian Thermosphere

DARRELL F. STROBEL AND GERALD R. SMITH[1]

Kitt Peak National Observatory[2], Tucson, Ariz. 85717

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ABSTRACT

A theoretical study is made to assess the importance of the solar EUV flux in the thermal energy balance of the Jovian thermosphere. A global averaged vertical temperature contrast in the thermosphere of 15K is calculated and the mesopause is located at a particle density of 5×10^{13} cm^{-3}. Thus, the upper atmosphere of Jupiter is approximately isothermal. At the mesopause IR cooling by C_2H_2 is an order of magnitude more important than IR cooling by CH_4. Only the location of the mesopause is a sensitive function of the IR cooling agent in the upper atmosphere. The exospheric temperature depends principally on the mesopause temperature and the solar flux. Eddy heat transport plays a negligible role in the thermal energy balance of the Jovian thermosphere. For the thermospheres of Saturn and Titan the global averaged vertical temperature contrasts are estimated to be ~10K and 90K, respectively, if their compositions are similar to Jupiter's and the same physics is applicable.

1. Introduction

From the occultation of Beta Scorpii by Jupiter, Hubbard *et al.* (1972) interpret temperatures in the Jovian thermosphere as high as 300K. Large thermospheric scale heights were, however, obtained on only two of their three best occultation events. In his review on the Jovian upper atmosphere, Hunten (1969) questioned the validity of the previously published thermal structure calculations for the Jovian thermosphere (Gross and Rasool, 1964; McGovern, 1968) and suggested the possibility of a substantially hotter Jovian thermosphere. Gross and Rasool (1964) assumed that CH_4 provided the IR cooling and found the mesopause at the 3×10^{14} cm^{-3} level. The temperature rise above the mesopause ($\Delta_v T$), defined as the exospheric temperature (T_∞) minus the mesopause temperature (T_0), was calculated to be ~12K for a hydrogen-dominated thermosphere with a heating efficiency of 50%. This small $\Delta_v T$ (when compared to the Earth) was attributed to the reduced solar flux incident on the Jovian atmosphere (by a factor of 27), the high thermal conductivity of H_2 and He, and the small scale heights in the Jovian thermosphere. In contrast, McGovern (1968) assumed that C_2H_6 was the IR radiating molecule on the basis of Cadle's (1962) photochemical studies and found $\Delta_v T\approx50$K for moderate solar conditions, a heating efficiency of 50%, and overhead sun. McGovern and Burk (1972) updated the previous model of McGovern (1968) with the recent EUV fluxes of Hinteregger (1970), the heating efficiency of 0.86 calculated by Henry and McElroy (1969), and IR cooling by CH_4 based on the photochemical study of Strobel (1969). For moderate solar conditions they obtained $\Delta_v T\approx30$K without transport of heat by eddy conduction. In this model the mesopause was located at the 10^{14} cm^{-3} level. With eddy conduction included in the model $\Delta_v T\approx18$K for an eddy coefficient of 10^6 cm^2 sec^{-1}.

Shimizu (1971), in his study of the Jovian upper atmosphere, obtained a global mean exospheric temperature of ~160K for a mesopause temperature of 140K with the heating efficiency of Henry and McElroy (1969) but with the earlier solar EUV fluxes of Hinteregger *et al.* (1965). Infrared cooling by polyatomic molecules was neglected in the calculation. As McGovern and Burk (1972) pointed out, a crucial parameter governing thermal structure calculations is the separation distance between the source (EUV heating) and the sink (IR cooling by polyatomic molecules). In the model of Shimizu (1971) the lower boundary located at the 3×10^{14} cm^{-3} level was equivalent to the mesopause. Shimizu calculated a negligible diurnal temperature variation in the Jovian thermosphere (<6K for solar maximum conditions).

Thus, the previous theoretical investigations do not agree with one another and are deficient in the description of IR cooling by polyatomic molecules. With the possibility of high exospheric temperatures observed on Jupiter it is imperative to determine to what extent the EUV flux can heat the Jovian thermosphere. Although the propagation of tidal and gravity waves from the lower atmosphere could, in principle, transport suffi-

[1] Present affiliation: Lunar Science Institute, Houston, Tex.

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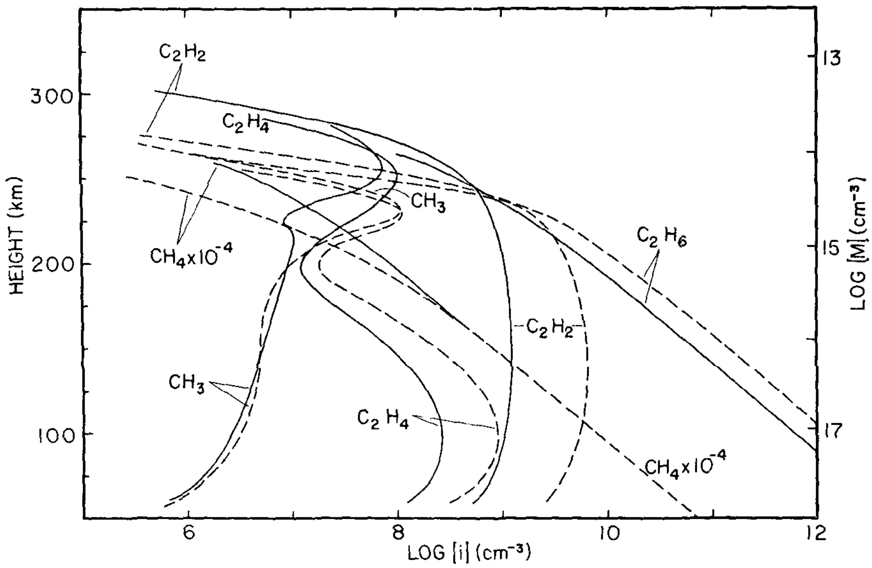

FIG. 1. Hydrocarbon density profiles from the model atmospheres of Strobel (1973) for $K=5\times10^5$ cm^2 sec^{-1} (solid lines) and $K=1\times10^5$ cm^2 sec^{-1} (dashed lines) as a function of height and/or total particle density.

cient energy to heat the thermosphere to 300K, it is important to assess what contribution the solar EUV flux makes. In this paper we present thermal structure calculations for the Jovian thermosphere based on the models of Strobel (1973) for the hydrocarbon photochemistry. Particular attention is devoted to an accurate description of IR cooling by polyatomic molecules. C_2H_2 is found to be the most important IR radiator and the global averaged vertical temperature contrast in the thermosphere is ~15K. In view of the short radiative time constants of C_2H_2, heat transport by eddy conduction is negligible.

2. Model

The model atmosphere adopted for this study has been developed by Strobel (1973) and consists of an isothermal atmosphere at 150K with 90% H_2, 10% He, and a CH_4 mixing ratio of 7×10^{-4} (by volume). The calculated C_2H_6 mixing ratio is $\sim10^{-5}$ and the C_2H_2 concentration $\sim10^9$ cm^{-3} throughout the upper stratosphere and lower mesosphere. In Fig. 1 the model results are illustrated for eddy diffusion coefficients of $K=5\times10^5$ and 1×10^5 cm^2 sec^{-1}. Wallace and Hunten (1973) obtained eddy diffusion coefficients of this magnitude in their interpretation of the Lyman-α albedo measurement by Moos and Rottman (1972). The potentially important molecules which radiate in the infrared are CH_4, C_2H_2, C_2H_4 and C_2H_6. In addition, NH_3 should be considered. However, in view of the confirmation of an underlying continuum in the absorption by NH_3 above 2000 Å (Dick and Ziko, 1973), the photochemical lifetime of NH_3 is very short when compared to the mixing time. As a consequence we do not expect large concentrations of NH_3 at the mesopause, even if its mixing ratio is 3×10^{-7} in the lower stratosphere (Hogan *et al.*, 1969).

Gillett *et al.* (1969) observed Jupiter in the spectral range 2.8–14 μ. For the stratosphere and mesosphere they suggest a temperature $\geqslant$145K. Hubbard *et al.* (1972) report mean scale heights of 24, 24 and 31 km for the mesosphere from the occultation of Beta Scorpii by Jupiter. Based on a solar abundance for He and H_2, a scale height of 24 km is equivalent to a temperature of 160K. Detailed thermal calculations by Hogan *et al.* (1969) suggest an isothermal stratosphere of 140K. The available evidence strongly supports an isothermal stratosphere and mesosphere of ~150K. Near the mesosphere we assume that the temperature decrease is small and adopt a mesopause temperature of 140K for our thermal structure calculations.

With the solar EUV flux as the source of heat energy in the Jovian thermosphere, its thermal structure can be calculated by the Chamberlain (1962) method. The heat sink is IR cooling by polyatomic molecules near the mesopause. The source and sink are separated by a considerable distance and energy is transported from the source to the sink by thermal conduction. For a rapidly rotating planet only the globally averaged thermal structure is of interest. To obtain a global average the solar fluxes are reduced by a factor of 2 and the attenuation of radiation is evaluated at a zenith angle of 60°. If the redistribution of thermal energy proceeds slowly in the thermosphere, then we would expect the equatorial exospheric temperature to be somewhat larger, i.e., $\sim(T_0+2\Delta_v T)$. The appropriate steady-state equation that describes the heat balance is (Chamberlain, 1962)

$$\kappa\frac{dT}{dz}=\frac{\mu_0}{2}\int \epsilon_\lambda F_\infty(\lambda)[1-\exp(-\tau_\lambda/\mu_0)]d\lambda - \int_z^\infty \sum_i R_i(z')dz', \quad (1)$$

where κ is the average thermal conductivity, $\mu_0=\cos 60°$, ϵ_λ is the heating efficiency, τ_λ the optical depth, $F_\infty(\lambda)$ the solar EUV flux incident at the top of the atmosphere per unit wavelength interval, and R_i the infrared cooling rate by constituent i. The wavelength integral in (1) is divided into 19 wavelength intervals.

For the solar flux input the tabulation given by Hinteregger (1970) was used. The flux at Lyman α is based on a flux of 5.5 eV cm^{-2} sec^{-1} at 1 au. In Table 1, the solar flux incident at the top of the Jovian atmosphere and the absorption cross sections for H_2, He and CH_4 used in the calculation are listed. In the wavelength interval 850–1100 Å only the fraction of the solar flux absorbed by H_2 in the Lyman and Werner bands is included. A small amount of energy absorbed by H atoms below 912 Å is neglected in the calculation. The heating efficiency ϵ_λ is based on the study of Henry and McElroy (1969) below 1100 Å. At Lyman α, which is absorbed only by CH_4 in the model (absorption by C_2H_2 is negligible), we estimate that approximately 20% of the dissociated CH_4 molecules recombine locally and adopt a heating efficiency of 0.65.

At low temperatures the thermal conductivity of H_2 depends approximately linearly on temperature (Roder and Diller, 1970; Hanley *et al.*, 1970) and $\kappa_{H_2}=68.6\,T$ [ergs cm^{-1} sec^{-1} $(°K)^{-2}$] adequately represents the experimental data. For He, $\kappa_{He}=890\,T^{\frac{1}{2}}$ [ergs cm^{-1} sec^{-1} $(°K)^{-\frac{3}{2}}$] (Chapman and Cowling, 1970; O'Neal and Brokaw, 1962). The average thermal conductivity is calculated in the manner described by Cowling *et al.* (1963).

In the Jovian upper atmosphere the mechanism for the loss of translational energy (heat) is the collisional excitation of the vibrational levels of molecules and the subsequent radiative transition to a lower vibrational level with the emission of an IR photon. With $T\approx 150$K only collisional excitation of the first vibrational level will be important. Of the molecules present in the Jovian atmosphere which are capable of radiation in the infrared (CH_4, C_2H_2, C_2H_4, C_2H_6, NH_3) only CH_4 and C_2H_2 need to be included in the calculation of the IR cooling rate. CH_4 is important because it has the largest concentration and radiates at 7.7 μ (ν_4 bending mode), while C_2H_2 has the next largest concentration and its first vibrational level (ν_5 mode) is at a low energy (equivalent to 13.7 μ) and thus has a high probability of collisional excitation.

The rate of radiative cooling is given by

$$R_i=h\nu_i A_i n_i^* \quad (2)$$

for each constituent i, where h is Planck's constant, ν_i the frequency associated with the $v=1\rightarrow v=0$ vibrational transition, n_i^* the number density of molecules i in the $v=1$ level by collisional excitation, and A_i the transition probability for $v=1\rightarrow v=0$ transition. The transition probabilities are 2.56 sec^{-1} for 7.7 μ (Yardley and Moore, 1968) and 6.0 sec^{-1} for C_2H_2 at 13.7 μ (Gerlovin, 1967). The above value for A_{CH_4} is a factor of 3 less than the value used by McGovern and Burk (1972) who neglected the degeneracy of 3 associated with first vibrational level of CH_4.

We can assume that the population of the $v=1$ level is given by equilibrium considerations, i.e., the produc-

TABLE 1. Solar flux incident at top of Jovian atmosphere, heating efficiency, and absorption cross sections below 1216 Å (Hudson, 1971).

$\Delta\lambda$ (Å)	$F(\lambda)$ [erg cm^{-2} sec^{-1} $(\Delta\lambda Å)^{-1}$]	$\epsilon(\lambda)$	$\sigma(H_2)$ (cm^2)	σ(He) (cm^2)	$\sigma(CH_4)$ (cm^2)
0–50	3.6(−4)	0.95	1 (−21)	1.5(−20)	3.0(−20)
50–100	6.6(−3)	0.95	1 (−20)	2.9(−19)	5.0(−19)
100–150	2.4(−3)	0.95	3 (−20)	5.2(−19)	1.8(−18)
150–200	1.9(−2)	0.93	1.0(−19)	8.5(−19)	2.5(−18)
200–250	5.6(−3)	0.93	4.6(−19)	1.5(−18)	4.5(−18)
250–300	2.8(−4)	0.89	7.0(−19)	2.3(−18)	6.3(−18)
300–350	1.2(−2)	0.89	1.4(−18)	3.4(−18)	9.5(−18)
350–400	2.5(−3)	0.86	2.0(−18)	4.5(−18)	1.3(−17)
400–450	6.6(−4)	0.86	2.8(−18)	5.5(−18)	1.6(−17)
450–500	7.8(−4)	0.82	3.8(−18)	6.3(−18)	2.1(−17)
500–550	1.0(−3)	0.82	4.6(−18)	0	2.5(−17)
550–600	1.4(−3)	0.78	5.8(−18)	0	3.3(−17)
600–650	1.5(−3)	0.78	7.8(−18)	0	3.3(−17)
650–700	1.3(−4)	0.75	9.4(−18)	0	3.6(−17)
700–750	2.6(−4)	0.75	1.0(−17)	0	4.1(−17)
750–800	1.2(−3)	0.71	8.5(−18)	0	4.3(−17)
800–850	1.6(−3)	0.71	4.5(−18)	0	4.6(−17)
850–1100	4.1(−3)	0.67	3 (−17)	0	4.0(−17)
1216	1.6(−1)	0.65	0	0	1.8(−17)

tion rate equals the loss rate. Thus,

$$n_i^* = n_i \sum_j P_{0\to1}^{ij} Z_{ij} n_j / (A_i + \sum P_{1\to0}^{ij} Z_{ij} n_j), \qquad (3)$$

where n_i is the number density of constituent i, Z_{ij} the frequency of collisions per molecule j, $P_{0\to1}^{ij}$ the probability that a collision with molecule j will excite molecule i to the $v=1$ level, $P_{1\to0}^{ij}$ the probability that molecule i in the $v=1$ level will be deactivated by a collision with molecule j, and the summation is over major constituents. We assume a hard sphere model for Z_{ij}, i.e.,

$$Z_{ij} = \sigma_{ij}^2 \left(\frac{8\pi kT}{\mu}\right)^{\frac{1}{2}}, \qquad (4)$$

where $\sigma_{ij} = \frac{1}{2}(\sigma_i + \sigma_j)$ with σ_i, σ_j the molecular diameters, μ the reduced mass, and k Boltzmann's constant.

Under equilibrium conditions we can obtain a relationship between $P_{1\to0}^{ij}$ and $P_{0\to1}^{ij}$ from the principle of detailed balancing:

$$\frac{P_{0\to1}^{ij} Z_{ij}}{P_{1\to0}^{ij} Z_{ij}} = \frac{\tilde{\omega}_1}{\tilde{\omega}_0} \exp(-h\nu_i/kT), \qquad (5)$$

where $\tilde{\omega}_1$ and $\tilde{\omega}_0$ are the statistical weights of the $v=1$ and $v=0$ levels, respectively. For CH_4, $\tilde{\omega}_1=3$, $\tilde{\omega}_0=1$, and for C_2H_2, $\tilde{\omega}_1=2$, $\tilde{\omega}_0=1$. Generally, $P_{1\to0}^{ij}$ is the quantity deduced from the measurement of vibrational relaxation times and it is temperature dependent. The exact temperature dependencies for various collisions are still very uncertain. There is experimental support for the theoretical Landau-Teller expression

$$P_{1\to0}^{ij} = C_{ij} \exp(-B_{ij}/T^{\frac{1}{3}}), \qquad (6)$$

which we used to represent experimental data of CH_4. For our models only the collisional interactions of CH_4 and C_2H_2 with H_2 are important. The data of Eucken and Aybar (1940) were used to determine a value of 42 $(°K)^{\frac{1}{3}}$ for B_{CH_4,H_2} in expression (6). We chose C_{CH_4,H_2} to give a probability of 5×10^{-4} at 297K which Yardley *et al.* (1970) deduced from their measurements of the vibrational relaxation time of CH_4 in H_2. For C_2H_2 in H_2 no data are available. Two measurements for C_2H_2 in C_2H_2 are available; and the value of $P_{1\to0}$ ranges from 1×10^{-3} to 2×10^{-3} (Edmonds and Lamb, 1958; Lambert and Salter, 1959; Cottrell and McCoubrey, 1961). We expect that H_2 is an efficient quencher of C_2H_2 vibrational energy and assume $P_{1\to0}^{C_2H_2,H_2} \approx 10^{-3}$. The sensitivity of the thermal structure to this probability is explored.

Expression (2) can be written with the use of (3) and (5) as

$$R_i = \frac{h\nu_i A_i n_i \sum_j P_{1\to0}^{ij} Z_{ij} n_j \frac{\tilde{\omega}_1}{\tilde{\omega}_0} \exp(-h\nu_i/kT)}{A_i + \sum_j P_{1\to0}^{ij} Z_{ij} n_j}, \qquad (7)$$

which, in the region where vibrational equilibrium breaks down, i.e.,

$$A_i \gtrsim \sum_j P_{1\to0}^{ij} Z_{ij} n_j,$$

reduces to

$$R_i \approx h\nu_i n_i \sum P_{1\to0}^{ij} Z_{ij} n_j \frac{\tilde{\omega}_1}{\tilde{\omega}_0} \exp(-h\nu_i/kT). \qquad (8)$$

A comparison of these expressions with similar expressions given by McGovern and Burk (1972) reveals that they underestimated R_i by a factor n_i/n_L, where n_L is Loschmidt's number. This is due to an inappropriate substitution of the vibrational relaxation time at STP for mesopause conditions. In addition, McGovern and Burk omitted the statistical weight of the first CH_4 vibrational level [=3] in these expressions but included the vibrational relaxation time of H_2 in H_2 (i.e. $P_{1\to0}^{H_2,H_2}$) in the IR cooling rate for CH_4.

The model atmospheres of Strobel (1973) are used to specify the composition at the mesopause. Above the mesopause the density profiles for each constituent (H_2, He, CH_4) are consistently calculated with the temperature profile obtained from the integration of (1). For C_2H_2 we assumed that it has a constant mixing ratio with CH_4 above the mesopause. The steady-state continuity equation for the ith constituent is $d\phi(i)/dz \approx 0$, when the effects of chemistry are small. The flux $\phi(i)$ is given by (Colegrove *et al.*, 1966)

$$\phi(i) = -D_i\left[\frac{\partial n_i}{\partial z} + \left(\frac{1+\alpha_i}{T}\frac{\partial T}{\partial z} + \frac{1}{H_i}\right)n_i\right] - K\left[\frac{\partial n_i}{\partial z} + \left(\frac{1}{T}\frac{\partial T}{\partial z} + \frac{1}{H_{av}}\right)n_i\right], \qquad (9)$$

where K is the eddy diffusion coefficient, H_{av} the scale height of the mixed atmosphere, D_i the average molecular diffusion coefficient (averaged over major constituents), α_i the thermal diffusion factor, and H_i the scale height of constituent i. The mutual diffusion coefficients are tabulated in Strobel (1973). From Chapman and Cowling (1970) $\alpha_{H_2} \approx 0$, $\alpha_{He} = +0.145$, and $\alpha_{CH_4} = +0.25$. For the standard model we assume $K = 5\times10^5$ cm^2 sec^{-1} (Wallace and Hunten, 1973).

The three flux equations (9) and the heat balance equation (1) were linearized and integrated by a standard Runge-Kutta technique iteratively until convergence was achieved. Generally a vertical step size of 0.5 km and 10 iterations were sufficient to achieve convergence.

3. Numerical results and discussion

For reference purposes the model developed in the previous section with $T_0=140K$, $K=5\times10^5$ cm^2 sec^{-1} and $P^{C_2H_2,H_2}_{1\to0}=10^{-3}$, will be called the "standard model." Certain input parameters of the model will be adjusted to study the importance of various physical processes in the Jovian thermosphere. To interpret the results we extract the essential physics from Eq. (1) and with the use of scale analysis obtain a simple expression for Δ_vT. As we have mentioned earlier the source and sink of heat energy are well separated spatially. The scale height associated with the sink is much less than the scale height of the thermosphere and to a first approximation all the IR cooling can be assumed to occur at a distinct level in the atmosphere, the mesopause. The solar EUV flux is mostly absorbed several thermospheric scale heights above the mesopause. Lyman α, however, is absorbed in the vicinity of the mesopause and thus does not contribute to the temperature rise above the mesopause. With $\int Qdz$ equal to the integrated heating rate due to the solar EUV flux (except for Lyman α), z_Q equal to the height above which one-half this heating occurs (equivalent to the height where the vertical H_2 column density is 9×10^{17} cm^{-2}), and z_0 the height of the mesopause, a scale analysis of (1) yields

$$\Delta_vT=T_\infty-T_0=\frac{z_Q-z_0}{\kappa}\int Qdz. \tag{10}$$

Similar expressions were derived earlier by Rasool *et al.* (1966) and Gross (1972). Thus, we expect the temperature contrast in the thermosphere to be linearly proportional to the integrated heating rate and the separation distance between source and sink, but inversely proportional to the thermal conductivity.

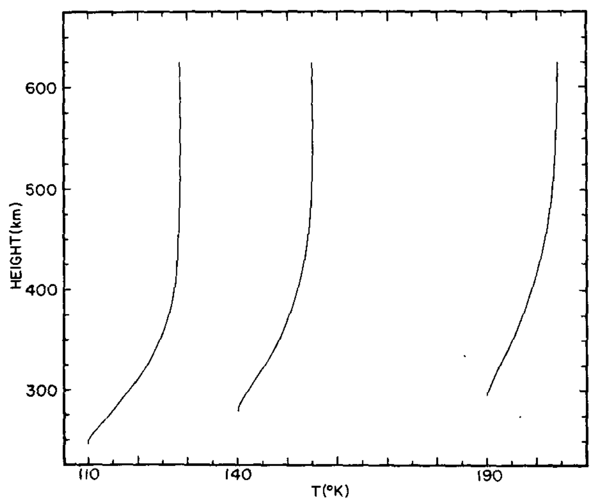

FIG. 2. Temperature profiles as a function of the mesopause temperature. The standard model has a mesopause temperature of 140K.

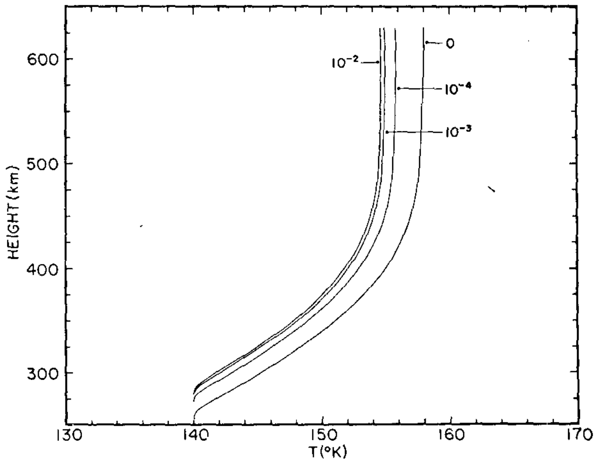

FIG. 3. Temperature profiles as a function of the probability of collisional deactivation of C_2H_2 ($v=1$) with H_2. The curve labelled 10^{-3} is the standard model while the curve labelled 0 is identical to a model without IR cooling by C_2H_2.

In Fig. 2 the temperature profile for the standard model is illustrated. The thermosphere is almost isothermal. The small temperature contrast is due to the low solar EUV flux, the high thermal conductivity of H_2, and the small scale heights in the Jovian thermosphere as pointed out by Gross and Rasool (1964). For the standard model $z_Q=395$ km, $z_0=280$ km, and $\int Qdz=1.3\times10^{-2}$ ergs cm^{-2} sec^{-1}. Substitution of these values into the simple expression (10) yields $\Delta_vT\approx15K$ in excellent agreement with the computer result. The mesopause z_0 occurs at a density level of $N_0\approx5\times10^{13}$ cm^{-3}, which is lower than the densities calculated in previous investigations.

Also shown in Fig. 2 is the sensitivity of Δ_vT to the mesopause temperature. With $T_0=110$ and 190K, we calculate $\Delta_vT=18$ and 14K, and $N_0=1.6\times10^{14}$ and 2.7×10^{13} cm^{-3}, respectively. Expression (10) yields identical results for Δ_vT. Thus, the temperature contrast is somewhat larger for smaller T_0 and it is tempting to attribute this to the linear temperature dependence of the H_2 thermal conductivity. Normally we expect the separation distance to be given by a numerical factor times the scale height which is also a linear function of T and would conclude that Δ_vT is independent of temperature. However, the mixing ratios of CH_4 and C_2H_2 with H_2 are not constant with height near the mesopause in the model and the composition at the mesopause as well as its location are functions of T_0. The net result is that the separation distance is not as sensitive to temperature changes as κ_{H_2}.

The sensitivity of the thermal structure of $P^{C_2H_2,H_2}_{1\to0}$ is illustrated in Fig. 3. Essentially T_∞ is independent of $P^{C_2H_2,H_2}_{1\to0}$ for the range of values considered. With

$P_{1\to0}^{C_2H_2,H_2}=10^{-2}$ and 10^{-4}, $N_0=5\times10^{13}$ and 7.5×10^{13} cm^{-3}. Thus, only the location of the mesopause is sensitive to $P_{1\to0}^{C_2H_2,H_2}$, with the higher its value, the higher the mesopause. Again expression (10) gives identical results. For $P_{1\to0}^{C_2H_2,H_2}\geqslant10^{-3}$ we find that the first vibrational level of C_2H_2 is almost in vibrational equilibrium at the mesopause, i.e.,

$$A_{C_2H_2}\ll P_{1\to0}^{C_2H_2,H_2}Z_{C_2H_2,H_2}n_{H_2},$$

and thus $R_{C_2H_2}$ is independent of $P_{1\to0}^{C_2H_2,H_2}$ [cf. Eq. (8)]. In view of the low solar EUV flux incident on the Jovian atmosphere, C_2H_2 is still capable of radiating this energy away while essentially in vibrational equilibrium.

The presence of C_2H_2 in the Jovian atmosphere is known only on the basis of theoretical calculations. In Fig. 3 we also present a temperature profile calculated with IR cooling by CH_4 only. The temperature contrast is 18K, as expected from (10), while the mesopause is at a level where $N_0=1.1\times10^{14}$ cm^{-3}. This higher density level is required because CH_4 is an order of magnitude less efficient than C_2H_2 in radiating IR energy away. We can conclude that T_∞ is not sensitive to the magnitude of the C_2H_2 concentration or the probability $P_{1\to0}^{C_2H_2,H_2}$.

In Fig. 4 the sensitivity of T_∞ to the eddy diffusion coefficient through its effect on the model atmosphere is illustrated. With $K=10^5$ cm^2 sec^{-1}, $\Delta_vT=18$K and the mesopause is at 260 km where $N_0=1.2\times10^{14}$ cm^{-3}. We conclude that T_∞ is essentially independent of K. Also illustrated in Fig. 4 is the sensitivity of T_∞ to the incident solar flux. From (10) we expect Δ_vT to be proportional to the flux and the detailed computer calculations confirm this expectation. With the solar flux increased by a factor of 2, Δ_vT increases from 15 to 31K. For the larger flux $z_Q=400$ km, $z_0=275$ km and $N_0=6.1\times10^{13}$ cm^{-3}. This solution is representative of solar maximum conditions.

McGovern and Burk (1972) emphasized the importance of eddy heat transport in the Jovian upper atmosphere. The analysis of Wallace and Hunten (1973) indicates that $K<10^6$ cm^2 sec^{-1}. For the standard model with $K=5\times10^5$ cm^2 sec^{-1} the time constant for mixing (H_{av}^2/K) is $\tau_{mix}\approx10^7$ sec. For eddy heat transport to be important McElroy (1967) argued that the radiative time constant τ_R must be greater than τ_{mix}. At the mesopause the radiative time constant is 10^6 sec while the corresponding radiative time constant at the turbopause is 6×10^6 sec. Consequently, we expect eddy heat transport to play a negligible role in the thermal structure of the Jovian thermosphere and accordingly have not included it in our model.

4. Summary and concluding remarks

If solar EUV heating is the major source of thermal energy, we conclude that the Jovian thermosphere is essentially isothermal with a global averaged vertical temperature contrast of ~15K for moderate solar conditions. For solar maximum conditions we estimate this quantity to be ~30K. If redistribution of thermal energy in the thermosphere is negligible, Δ_vT could be as large as 60K (an upper limit) at equatorial latitudes for solar maximum conditions. Thus, $T_\infty<200$K for the probable mesopause temperatures of ~140K. This upper limit is substantially less than the largest exospheric temperatures deduced by Hubbard *et al.* (1972) from occultation of Beta Scorpii by Jupiter. If the interpretation by Hubbard *et al.* is correct then some other mechanism than solar EUV heating is responsible for the high temperatures in the Jovian thermosphere. However, the larger thermospheric scale heights were obtained on only two of their three best occultation events and could be due, in part, to systematic errors.

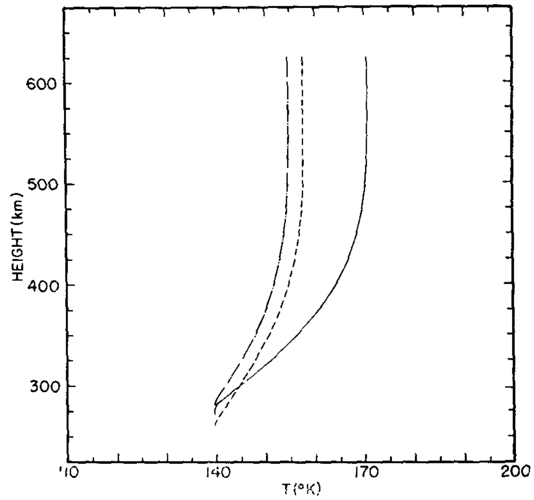

Fig. 4. Sensitivity of the exospheric temperature to input parameters. The standard model is given by dot-dash curve. The solid curve assumes a factor of 2 increase in the solar flux and the dashed curve reflects a factor of 5 decrease in the eddy diffusion coefficient, i.e., $K=1\times10^5$ cm^2 sec^{-1}.

On the basis of our model results we find that Δ_vT is only a sensitive function of the solar flux. Thus, the exospheric temperature is dependent principally on the solar flux and the mesopause temperature. Only the location of the mesopause is a sensitive function of the IR cooling agent in the upper atmosphere. In addition, the location of the mesopause depends on the solar flux, mesopause temperature, and the eddy diffusion coefficient.

A comparison of our results with the previous study of McGovern and Burk (1972) indicates agreement on Δ_vT for the case without eddy heat transport if their results are reduced by a factor of 2 to correct for the overhead sun conditions assumed in their calculation. Our model, however, predicts a mesopause at a much lower total particle density, as would be expected from the inclusion of C_2H_2 cooling in our model and the underestimate of the cooling term by McGovern and Burk. In the standard model C_2H_2 radiates approximately an order of magnitude more energy than CH_4

does at the mesopause. A comparison of our results with other investigations is not warranted because the input parameters are substantially different.

In view of the surprising accuracy of expression (10) it is tempting to estimate the vertical temperature contrasts in the thermospheres of Saturn and Titan. It must be remembered that in (10) we used the values of z_Q and z_0 from the computer results. While z_Q can be readily estimated on the basis that the vertical H_2 column density is 9×10^{17} cm^{-2} at this level, the location of z_0 is much more difficult. Instead we proceed as follows. The separation distance is a function of the density distribution in the thermosphere. We expect it to be approximately a linear function of H_{av}. For the standard model $z_Q-z_0=115$ km, which is in terms of scale heights, $4.6H_{av}$. Substitution of this result into (10) yields

$$\Delta_v T=\frac{4.6k}{\kappa_0 m_{av} g_0}\int Q dz, \tag{11}$$

where m_{av} is the mean molecular mass, $\kappa_0=\kappa_{H_2}T^{-1}$, k is Boltzmann's constant, and g_0 the gravitational acceleration in the thermosphere. Expression (11) is independent of the temperature. On Saturn the solar flux is 0.3 its intensity at Jupiter. If we assume Saturn has a composition similar to Jupiter then $\Delta_v T\approx10$K. The smaller flux on Saturn is partially compensated by a smaller g_0. Thus, we expect Saturn to have essentially an isothermal thermosphere.

The atmospheric composition of Titan is uncertain. In his recent review of this subject Hunten (1972) suggests that N_2 may be the major constituent in the lower atmosphere of Titan. Since N_2 is heavier than CH_4 and H_2 it is unlikely that N_2 is the major constituent in the thermosphere. If it were we would predict from (11) that $\Delta_v T\approx30$K, assuming the high heating efficiency of H_2 which is probably the major constituent in the thermosphere. If we assume that the compositions of the thermospheres of Jupiter and Titan are similar and that the same physics is applicable, then we calculate $\Delta_v T\approx90$K from (11). This high value is due principally to the small value of g_0 on Titan. From an evolutionary point of view it is interesting to note that as the CH_4/H_2 mixing ratio decreases, the separation distance will increase and so will $\Delta_v T$ and vice versa. Since H_2 can readily escape from Titan, Jeans escape may regulate the CH_4/H_2 mixing ratio in the upper atmosphere of Titan.

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