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**Parameterization of the Atmospheric Heating
Rate from 15 to 120 km Due to O₂ and O₃
Absorption of Solar Radiation**

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November 1976

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PARAMETERIZATION OF THE ATMOSPHERIC HEATING RATE
FROM 15 TO 120 KM DUE TO O₂ AND O₃
ABSORPTION OF SOLAR RADIATION

INTRODUCTION

In order to numerically simulate the earth's upper atmospheric circulation, accurate and computationally efficient parameterizations of solar radiative heating are required. Of major interest is the solar radiative heating by ozone absorption in the Hartley region (2000-3000Å), Huggins bands (3000-3500Å) and the Chappius bands (4500-7500Å). Above the mesopause O₂ absorption of solar uv radiation in the Schumann-Runge bands (1750-2050Å) and Schumann-Runge continuum (1250-1750Å) must also be included.

For ozone heating rates two different parameterizations have been previously developed. Lindzen and Will (1973) assumed that the O₃ absorption cross sections are either constant or have an exponential variation over individual wavelength intervals. With these assumptions, they obtained simple analytic formulas for the O₃ heating rate. The advantage of this method is that improved solar flux and/or cross section data can easily be incorporated into the parameterization scheme. An alternate approach has been developed by Lacis and Hansen (1974) for general circulation models. They found analytic expressions for the O₃ heating rate profiles by numerical fits to exact profiles. However, to incorporate revised solar flux and/or cross section data this method requires a repetition of their fitting procedures to obtain new numerical coefficients. This approach is obviously not as flexible in some respects as the Lindzen and Will (1973) formulas. Accordingly, the latter is adopted to represent O₂ and O₃ heating rates by insolation from 15 to 120 km.

Note: Manuscript submitted October 18, 1976.

EXACT HEATING RATE CALCULATION

To develop parameterizations for any atmospheric circulation model, it is best to have "exact" or detailed calculations available to assess their accuracy. The solar fluxes and the O_2 and O_3 absorption cross sections adopted for the exact calculation are tabulated in Table 1. Since we will indicate how to incorporate improved fluxes and cross sections in the parameterizations, we do not need to justify the selected input data (e.g., the controversial solar flux values in the 1750-2050 $\text{\AA}$ region).

The solar fluxes were selected from the following sources: Broadfoot (1972), Brueckner et al. (1976), CIAP Monograph 1, Donnelly and Pope (1973) and Smith and Gottlieb (1975). The O_2 and O_3 cross sections are based on Blake (1973), CIAP Monograph 1, Hudson (1971) and Hudson and Mahle (1972). Calculation of the O_2 and O_3 heating rates is straightforward for all wavelengths of interest with the exception of solar radiation penetration through the absorbing O_2 Schumann-Runge bands (1750-2050 $\text{\AA}$). McConnell (1974) has noted that transmission of solar radiation in each band i , Tr_i , can be adequately represented by

$$Tr_i = \exp \left\{ -(\gamma_i N_2 + \delta_i N_2^{1/2}) \right\} \quad (1)$$

where N_2 is the column density of O_2 along the solar radiation path, γ_i and δ_i are coefficients given in Table 2. The total O_2 heating rate in the Schumann-Runge bands (SRB) is

$$Q_{SRB}(O_2) = \sum_{i=1}^{19} F_i \sigma_i Tr_i [O_2] \quad (2)$$

where F_i is the solar flux integrated over each band, $[O_2]$ is the O_2 number density and the cross section (σ_i) is given by

$$\sigma_i^{-1} = \alpha_i + \beta_i N_2^{1/2} \quad (3)$$

with α_i and β_i tabulated in Table 2. An accuracy of within 20 percent of the experimental data of Hudson and Mahle (1972) can be achieved with these expressions and coefficients. The O_2 column density was computed using a 16 point Gaussian quadrature integration scheme.

Net heating rates (ϵQ) defined as the energy absorbed minus the chemical energy stored by the dissociated products were computed with efficiency factors,

$$\epsilon_j = \left(\frac{hc}{\lambda_j} - D \right) / \frac{hc}{\lambda_j} \quad (4)$$

where D is the dissociation energy of the absorbing molecules (1.05 eV for O_3 and 5.12 eV for O_2), λ_j is the wavelength of the photon, h is Planck's constant and c is the speed of light.

PARAMETERIZATION OF THE O₃ HEATING RATE

For the Chappius bands (c) we follow Lindzen and Will (1973) and write the O₃ heating rate (Q_c) as

$$\frac{Q_c}{[O_3]} = F_c \sigma_c e^{-\sigma_c N_3} \quad (5)$$

where [O₃] is the O₃ number density and N₃ its column density along the solar radiation path. We find that

$$\begin{aligned} F_c &= 3.7 \times 10^5 \text{ ergs cm}^{-2} \text{ sec}^{-1} \\ \sigma_c &= 2.85 \times 10^{-21} \text{ cm}^2 \end{aligned} \quad (6)$$

gives the best fit to exact calculations of Q_c. σ_c is 0.62 times the peak O₃ cross section at ~6000Å and F_c is 0.7 times the integrated flux over the Chappius bands. The net heating rate ε_cQ_c is obtained with λ_j = 6000Å for the efficiency factor ε_c from equation (4).

A similar approximation is appropriate for the Hartley region (Ha) from 2425-2775Å. Thus

$$\frac{Q_{Ha}}{[O_3]} = F_{Ha} \sigma_{Ha} e^{-\sigma_{Ha} N_3} \quad (7)$$

where

$$\begin{aligned} F_{Ha} &= 5460 \text{ ergs cm}^{-2} \text{ sec}^{-1} \\ \sigma_{Ha} &= 8.8 \times 10^{-18} \text{ cm}^2 \end{aligned} \quad (8)$$

with σ_{Ha} equal to 0.8 times the peak O_3 cross section at $\sim 2525\text{\AA}$ and F_{Ha} the integrated flux over the $2425\text{--}2775\text{\AA}$ interval. The net heating rate $\epsilon_{\text{Ha}} Q_{\text{Ha}}$ is calculated with $\lambda_j = 2500\text{\AA}$ in equation (4).

In the Huggins bands (Hu, defined here as the $2775\text{--}3600\text{\AA}$ interval) we assume, as Lindzen and Will (1973), that the O_3 cross section has an exponential variation

$$\sigma = \sigma_{\text{Hu}} e^{-M\lambda} \quad (9)$$

To obtain greater accuracy than Lindzen and Will (1973), we break the Huggins bands up into two intervals. The heating rate is

$$\frac{Q_{\text{Hu}}}{[\text{O}_3]} = \int_{\lambda_{\text{long}}}^{3600\text{\AA}} I_1 \sigma e^{-\sigma N_3} d\lambda + \int_{\lambda_{\text{short}}}^{\lambda_{\text{long}}} I_2 \sigma e^{-\sigma N_3} d\lambda$$

or

$$\frac{Q_{\text{Hu}}}{[\text{O}_3]} = \frac{1}{MN_3} \left\{ I_1 + (I_2 - I_1) \exp \left[-\sigma_{\text{Hu}} N_3 e^{-M\lambda_{\text{long}}} \right] - I_2 \exp \left[-\sigma_{\text{Hu}} N_3 e^{-M\lambda_{\text{short}}} \right] \right\} \quad (10)$$

where the atmosphere is optically thin at $3600\text{\AA}$. Numerically, an excellent fit to the exact heating rate is obtained with

$$I_1 = 59.2 \quad \text{ergs cm}^{-2} \text{sec}^{-1} \text{\AA}^{-1}$$

$$I_2 = 49.3 \quad \text{ergs cm}^{-2} \text{sec}^{-1} \text{\AA}^{-1}$$

$$M = 0.0127 \text{\AA}^{-1}$$

$$\lambda_{\text{short}} = 2805 \text{\AA}$$

$$\lambda_{\text{long}} = 3055 \text{ \AA} \quad (11)$$

$$\sigma_{\text{Hu}} = 0.0125 \text{ cm}^2.$$

The intensities I_1 and I_2 can be related to fluxes integrated over the respective wavelength intervals. $\Delta\lambda_1 = 3600 - \lambda_{\text{long}} = 345\text{\AA}$ and $\Delta\lambda_2 = \lambda_{\text{long}} - \lambda_{\text{short}} = 250\text{\AA}$. Thus, $F_1 = I_1 \Delta\lambda_1 = 2.04 \times 10^4 \text{ ergs cm}^{-2} \text{ sec}^{-1}$ and $F_2 = I_2 \Delta\lambda_2 = 1.23 \times 10^4 \text{ ergs cm}^{-2} \text{ sec}^{-1}$. From Table 1 the integrated flux over interval 1 is $4.4 \times 10^4 \text{ ergs cm}^{-2} \text{ sec}^{-1}$ and F_1 is 0.46 times this value, while the integrated flux over the 2775-3055 $\text{\AA}$ interval is $1.25 \times 10^4 \text{ ergs cm}^{-2} \text{ sec}^{-1}$ and F_2 is equal to this flux. In interval 1 the atmosphere is partially optically thin and all photons are not absorbed.

In the Herzberg continuum (2060-2425 $\text{\AA}$) both O_2 and O_3 absorb solar radiation and the principal region of heating occurs at 35-55 km. Adequate representation of this heating (Q_{Hz}) can be obtained with

$$Q_{\text{Hz}} = F_{\text{Hz}} \left\{ \sigma_{\text{Hz}}(\text{O}_2)[\text{O}_2] + \sigma_{\text{Hz}}(\text{O}_3)[\text{O}_3] \right\} \exp \left[-\sigma_{\text{Hz}}(\text{O}_2)N_2 - \sigma_{\text{Hz}}(\text{O}_3)N_3 \right] \quad (12)$$

and

$$F_{\text{Hz}} = 1.5 \times 10^3 \text{ ergs cm}^{-2} \text{ sec}^{-1}$$

$$\sigma_{\text{Hz}}(\text{O}_2) = 6.6 \times 10^{-24} \text{ cm}^2$$

$$\sigma_{\text{Hz}}(\text{O}_3) = 4.9 \times 10^{-18} \text{ cm}^2$$

$$\lambda_j = 2290\text{\AA} \text{ to calculate } \epsilon_{\text{Hz}}$$

where F_{Hz} is 0.79 times the integrated flux in this wavelength region.

The parameterizations for the Chappius, Huggins, and Hartley bands are accurate to better than 2 percent. With the inclusion of

the Herzberg continuum parameterization the accuracy for the summed O_3 heating rates decreases to 5 percent, primarily because equation (12) underestimates the actual heating rate below 42 km. In Figures 1 and 2 the individual contributions to the total and net heating rates, respectively, are illustrated based on the above parameterizations. They are diurnally-averaged heating rates at the equator during equinox. The model atmosphere used in the computations is given in Table 3. Conversion factors for heating rates in $^{\circ}K \text{ day}^{-1}$ to $\text{ergs cm}^{-3} \text{ sec}^{-1}$ are given in Table 4.

Above 45 km O_3 absorption in the Hartley region is the dominant heat source, whereas below 28 km the Chappius band absorption is dominant. In the intermediate region the Huggins bands dominate. The secondary peak in the heating rate at ~ 85 km corresponds to the secondary maximum in the O_3 concentration in the model atmosphere. Thus, thermodynamically, this $[O_3]$ peak is expected to be quite important and its absolute value must be accurately known. Absorption in the Herzberg continuum makes a small contribution to the heating rate.

PARAMETERIZATION OF THE O₂ HEATING RATE

The Schumann-Runge continuum (SRC) can be split up into two main regions: 1250-1520Å where the O₂ cross section $\sim 10^{-17}$ cm², and 1520-1750Å where the O₂ cross section is proportional to $e^{-M\lambda}$. For the 1250-1520Å region we may approximate the heating as

$$\frac{Q_{\text{SRC}}}{[\text{O}_2]} = F_{\text{SRC}} \sigma_{\text{SRC}} e^{-\sigma_{\text{SRC}} N_2} \quad (13)$$

with

$$F_{\text{SRC}} = 1.1 \text{ erg cm}^{-2} \text{ sec}^{-1}$$

$$\sigma_{\text{SRC}} = 1 \times 10^{-17} \text{ cm}^2$$

$$\epsilon_{\text{SRC}} = 0.41 \text{ for net heating}$$

where F_{SRC} is the integrated flux over this wavelength region and σ_{SRC} is the average cross section. For the 1520-1750Å region we divide it into two intervals with $\sigma(\text{O}_2) \propto e^{-M\lambda}$ and obtain a total heating rate of

$$\frac{Q_{\text{SRC}}}{[\text{O}_2]} = \frac{1}{N_2} \left\{ \frac{I_{\underline{l}}}{M} e^{-\sigma_{\underline{l}} N_2} + \frac{I_{\underline{s}} - I_{\underline{l}}}{M} e^{-\sigma_{\underline{m}} N_2} - \frac{I_{\underline{s}}}{M} e^{-\sigma_{\underline{s}} N_2} \right\} \quad (14)$$

where $\underline{l}$ denotes long wavelength end of spectrum, $\underline{s}$ denotes short wavelength end and $\sigma_{\underline{m}}$ denotes O₂ cross section at the junction of these intervals ($\sim 1660\text{\AA}$). The following values were found to give an excellent fit

$$\begin{aligned}
\frac{I_{\ell}}{M} &= 3.43 \text{ ergs cm}^{-2} \text{ sec}^{-1} \\
\frac{I_s}{M} &= 1.35 \text{ ergs cm}^{-2} \text{ sec}^{-1} \\
\sigma_{\ell} &= 2.9 \times 10^{-19} \text{ cm}^2 \\
\sigma_m &= 1.54 \times 10^{-18} \text{ cm}^2 \\
\sigma_s &= 1.1 \times 10^{-17} \text{ cm}^2
\end{aligned}
\tag{15}$$

$\frac{I_{\ell}}{M}$ is approximately 0.6 times the integrated solar flux in the 1660-1750 $\text{\AA}$ interval, while $\frac{I_s}{M}$ is approximately 0.5 times the solar flux in the 1520-1660 $\text{\AA}$ interval. The O_2 cross sections σ_{ℓ} , σ_m , and σ_s are approximately the values at 1750, 1660, and 1520 $\text{\AA}$, respectively. To compute the net heating rate we recommend

$$\begin{aligned}
\frac{\epsilon I_{\ell}}{M} &= 0.98 \text{ ergs cm}^{-2} \text{ sec}^{-1} \\
\frac{\epsilon I_s}{M} &= 0.43 \text{ ergs cm}^{-2} \text{ sec}^{-1} \\
\sigma_{\ell} &= 2.9 \times 10^{-19} \text{ cm}^2 \\
\sigma_m &= 1.7 \times 10^{-18} \text{ cm}^2 \\
\sigma_s &= 1.15 \times 10^{-17} \text{ cm}^2
\end{aligned}
\tag{16}$$

where $\epsilon \approx 0.3$.

The main contribution to atmospheric heating from the O_2 Schumann-Runge bands (SRB) occurs in the 60-100 km region. In view of the uncertainty in the solar flux magnitude in the Schumann-Runge bands coupled with the complexity of its transmission through the atmosphere, we demand only an accuracy of ± 20 percent in this parameterization. The following expression represents the total

heating rate in the 60-100 km region

$$\frac{Q_{\text{SRB}}}{[\text{O}_2]} = \frac{1}{aN_2 + bN_2^{1/2}} \quad (17)$$

where

$$\begin{aligned} a &= 0.143 \text{ cgs units} \\ b &= 9.64 \times 10^8 \text{ cgs units} \end{aligned} \quad (18)$$

and if $N_2 < 10^{18} \text{ cm}^2$, then

$$\frac{Q_{\text{SRB}}}{[\text{O}_2]} = 9.03 \times 10^{-9} \text{ ergs sec}^{-1} . \quad (19)$$

For the net heating rate we obtain

$$\begin{aligned} a &= 0.67 \text{ cgs units} \\ b &= 3.44 \times 10^9 \text{ cgs units} \end{aligned} \quad (20)$$

and if $N < 10^{18} \text{ cm}^2$, then

$$\frac{Q_{\text{SRB}}}{[\text{O}_2]} = 2.43 \times 10^{-19} \text{ ergs sec}^{-1} . \quad (21)$$

By appropriate scaling of both coefficients, heating rates for alternate solar flux values can be obtained.

The individual contributions to the O_2 heating rates from the above parameterizations are shown in Figures 1 and 2. Near 60 km the total O_2 heating rate is accurate only to ± 25 percent, but above 75 km it improves to within 5 percent. Heating in the Schumann-Runge bands is the dominant heat source between 88 and 96 km, while absorption in the SR continuum is most important above 96 km. The relative

importance of the SR bands in the 80-90 km region depends significantly on the O_3 concentration there.

The overall accuracy of the parameterized heating rates is ± 5 percent over the altitude region 15-120 km. Below approximately 80 km the $O(^3P)$ formed by O_3 and O_2 dissociation recombines quickly, and the actual heating rate of the atmosphere is the total photon energy absorbed. Above 80 km the $O(^3P)$ produced by O_3 and O_2 dissociation may be transported significantly in the vertical direction before recombining, and the actual heating rate is the net heating rate (ϵQ) plus the chemical energy released by locally recombining $O(^3P)$. To a good first approximation we can estimate the actual heating rate by summing the total O_3 heating rate and the net O_2 heating rate. In Figure 3 this estimated actual heating rate is illustrated for solstitial conditions. Only the latitudinal variation of solar radiation was included; the model atmosphere was invariant with latitude. Our heating rate agrees well with the results of Park and London (1974) when the comparison is made at the same density levels.

PARAMETERIZATION OF DIFFUSE SCATTERED SOLAR RADIATION

Solar radiation longward of $3000\text{\AA}$ is not strongly absorbed in the earth's atmosphere and can undergo multiple scattering in the atmosphere by molecules and particles. Fortunately, in atmospheric heating calculations the major scattering effects are in the Chappius bands region of the solar spectrum (Lacis and Hansen, 1974). Their results strongly suggest that the diffuse solar radiation can be modeled by a pure O_3 absorption region on top of a reflecting layer with an effective albedo ($\bar{\omega}_0$) that depends on the ground reflectivity (R_g) and lower atmosphere albedo (R_a) as follows:

$$\bar{\omega}_0 = R_a + [1 - R_a] \frac{0.856 R_g}{1 - 0.144 R_g} . \quad (22)$$

Let the vertical optical depth due to O_3 absorption be

$$\tau^* = \int_0^\infty \sigma n dz \quad (23)$$

where n is the O_3 number density, σ is its cross section, z is height, and $d\tau = -\sigma n dz$. With θ as the solar zenith angle and s as the distance along the solar radiation path (increasing in positive value with decreasing z), we define $\mu = \cos\theta$ and $\mu ds = -dz$. The intensity (I) of the solar radiation is separated into upward (I^+) and downward (I^-) components. The associated flux is

$$F = \int_{-1}^1 I \mu d\mu = \int_0^1 I^+ \mu d\mu + \int_{-1}^0 I^- \mu d\mu \quad (24)$$

and the corresponding heating rate is

$$Q = -\nabla \cdot F = - \int_{-1}^1 \frac{dI}{dz} \mu d\mu \quad (25)$$

for a plane parallel atmosphere. For visible sunlight in the purely absorbing atmosphere the equation of transfer is simply

$$\mu \frac{dI}{d\tau} = I \quad (26)$$

since atmospheric thermal emission is negligible. Equation (26) has the solution

$$I = I_0 e^{\frac{\tau}{\mu}} \quad (27)$$

For the downward intensity component the boundary condition is applied at the top of the atmosphere and is

$$I^-(\tau = 0, \mu) = F_0 \delta(\mu + \mu_0) \quad (28)$$

where F_0 is the downward directed solar flux with direction μ_0 . Thus

$$I^-(\tau, \mu) = F_0 \delta(\mu + \mu_0) e^{\frac{\tau}{\mu}}, \mu < 0 \quad (29)$$

For the upward intensity component the boundary condition is applied at the reflecting surface ($\tau = \tau^*$) and is a Lambert surface with albedo ($\bar{\omega}_0$),

$I^+(\tau^*, \mu)$ is isotropic

$$F^+ = \bar{\omega}_0 F^- \text{ at } \tau = \tau^* \quad (30)$$

Then at τ^*

$$F^+ = \int_0^1 I^+(\tau^*, \mu) \mu d\mu = \frac{1}{2} I^+(\tau^*, \mu) = \omega_0 \int_{-1}^0 I^-(\tau^*, \mu) \mu d\mu$$

or with equation (24)

$$I^+(\tau^*, \mu) = 2\omega_0 \mu_0 F_\theta e^{-\frac{\tau^*}{\mu_0}} \quad (31)$$

and

$$I^+(\tau, \mu) = 2\omega_0 \mu_0 F_\theta e^{-\frac{\tau}{\mu_0}} e^{-\frac{(\tau^* - \tau)}{\mu}}, \quad \mu > 0. \quad (32)$$

Since $d\tau = -\sigma n dz$, equation (25) becomes upon substitution of equation (26)

$$Q = \sigma n \int_{-1}^1 I d\mu$$

and integration over all angles with the upward (32) and downward (29) components of intensity gives

$$Q = F_\theta e^{-\frac{\tau}{\mu_0}} \sigma n + 2\omega_0 \mu_0 F_\theta e^{-\frac{\tau^*}{\mu_0}} E_2(\tau^* - \tau) \sigma n \quad (33)$$

where the exponential integral E_2

$$E_2(x) = \int_0^1 d\mu e^{-\frac{x}{\mu}}$$

represents the transmission of the reflected light off the surface. This second term in equation (33) is thus the heating due to diffuse

reflected and scattered solar radiation, whereas the first term in equation (33) represents direct solar radiation heating.

Lacis and Hansen (1974) recommend a simple approximation for the transmission function E_2 . It is

$$E_2(\tau^* - \tau) \simeq e^{-(\tau^* - \tau)M}$$

where M is the magnification factor for the vertical optical depth and has an effective value of 1.9 for diffuse radiation.

Comparisons of their detailed calculations with the results obtained from the following expression

$$Q = F_0 \sigma n \left\{ e^{-\frac{\tau}{\mu_0}} + 2\bar{\omega}_0 \mu_0 e^{-\frac{\tau^*}{\mu_0}} e^{-1.9(\tau^* - \tau)} \right\} \quad (34)$$

show good agreement for diffuse radiative heating (within 10 percent). If the effective albedo is $\bar{\omega}_0 = 0.25$, a reasonable global average, then the O_3 heating rate from Chappius bands absorption is increased by 30 percent throughout the ozone layer due to diffuse solar radiation. This description of diffuse radiation should also prove adequate for the 3000-4000 $\text{\AA}$ solar uv radiation.

SUMMARY

The atmospheric heating rates due to O_2 and O_3 absorption of solar radiation have been successfully parameterized with an accuracy of ± 5 percent from 15 to 120 km. In addition, the diffuse solar radiation produced by multiple scattering and ground reflection has been adequately described with a simple radiative transfer model of a purely absorbing layer on top of a reflecting layer. These parameterizations are suitable for use in complex numerical models of atmospheric circulation.

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Table 1: Solar Fluxes and Absorption Cross Sections*

$\lambda(\text{\AA})$	Flux (ergs cm ⁻² sec ⁻¹)	$\sigma(O_2)(\text{cm}^2)$	$\sigma(O_3)(\text{cm}^2)$
7500	1.27(4)		3.5(-22)
7400	1.30(4)		3.8(-22)
7300	1.34(4)		4.2(-22)
7200	1.37(4)		5.4(-22)
7100	1.40(4)		6.5(-22)
7000	1.43(4)		8.2(-22)
6900	1.47(4)		1.0(-21)
6800	1.50(4)		1.3(-21)
6700	1.54(4)		1.6(-21)
6600	1.54(4)		2.0(-21)
6500	1.56(4)		2.4(-21)
6400	1.62(4)		2.9(-21)
6300	1.65(4)		3.4(-21)
6200	1.68(4)		3.9(-21)
6100	1.72(4)		4.5(-21)
6000	1.75(4)		4.6(-21)
5900	1.78(4)		4.0(-21)
5800	1.82(4)		4.3(-21)
5700	1.83(4)		4.3(-21)
5600	1.83(4)		3.5(-21)
5500	1.85(4)		3.1(-21)
5400	1.89(4)		2.7(-21)
5300	1.89(4)		2.3(-21)
5200	1.85(4)		1.7(-21)
5100	1.87(4)		1.5(-21)
5000	1.93(4)		9.4(-22)
4900	1.92(4)		6.7(-22)
4800	1.94(4)		5.7(-22)
4700	1.99(4)		2.7(-22)
4600	2.00(4)		2.4(-22)
4500	1.97(4)		1.2(-22)
3550	9.5(3)		3.5(-22)
3450	8.9(3)		1.0(-21)
3350	9.0(3)		4.2(-21)
3250	7.8(3)		1.5(-20)
3150	6.4(3)		6.2(-20)
3075	2.6(3)		1.5(-19)
3000	3.9(3)		3.5(-19)
2925	5.2(3)		1.2(-18)
2825	2.4(3)		3.3(-18)
2725	2.4(3)		6.8(-18)
2625	1.9(3)		1.0(-17)
2525	8.1(2)		1.1(-17)
2450	3.5(2)		9.8(-18)
2400	2.9(2)	5.0(-25)	8.2(-18)
2350	2.9(2)	1.4(-24)	6.4(-18)
2300	3.1(2)	3.3(-24)	4.5(-18)
2250	3.4(2)	5.3(-24)	3.0(-18)

Table 1: Solar Fluxes and Absorption Cross Sections* - Cont.

$\lambda(\text{\AA})$	Flux (ergs cm ⁻² sec ⁻¹)	$\sigma(0_2)(\text{cm}^2)$	$\sigma(0_3)(\text{cm}^2)$
2200	2.9(2)	7.6(-24)	1.8(-18)
2150	2.4(2)	9.6(-24)	1.0(-18)
2100	1.5(2)	1.1(-23)	5.5(-19)
2060	2.0(1)	1.3(-23)	3.8(-19)
2025	1.7(1)	See Table 2	3.3(-19)
2000	1.4(1)	"	3.1(-19)
1985	7.0(0)	"	3.3(-19)
1972	5.8(0)	"	3.6(-19)
1947	1.0(1)	"	4.1(-19)
1924	7.0(0)	"	4.5(-19)
1902	6.5(0)	"	5.2(-19)
1882	5.2(0)	"	5.9(-19)
1863	4.2(0)	"	6.5(-19)
1846	2.8(0)	"	6.8(-19)
1830	2.7(0)	"	7.0(-19)
1816	2.5(0)	"	7.3(-19)
1804	1.8(0)	"	7.5(-19)
1793	1.3(0)	"	7.7(-19)
1783	1.2(0)	"	7.9(-19)
1775	8.1(-1)	"	8.1(-19)
1769	6.7(-1)	"	8.2(-19)
1763	1.3(0)	"	8.2(-19)
1750	1.0(0)	"	8.3(-19)
1740	1.7(0)	3.7(-19)	
1720	1.5(0)	5.9(-19)	
1700	1.3(0)	8.5(-19)	
1680	8.7(-1)	1.2(-18)	
1660	7.7(-1)	1.8(-18)	
1640	5.6(-1)	2.5(-18)	
1620	4.0(-1)	3.4(-18)	
1600	3.2(-1)	4.7(-18)	
1580	2.9(-1)	6.0(-18)	
1560	3.4(-1)	7.3(-18)	
1540	3.3(-1)	8.5(-18)	
1520	2.0(-1)	1.0(-17)	
1500	1.5(-1)	1.1(-17)	
1480	1.3(-1)	1.2(-17)	
1460	1.1(-1)	1.3(-17)	
1440	8.3(-2)	1.5(-17)	
1420	7.0(-2)	1.5(-17)	
1400	1.3(-1)	1.4(-17)	
1380	4.8(-2)	1.3(-17)	
1360	6.3(-2)	8.0(-18)	
1340	1.2(-1)	2.3(-18)	
1320	4.3(-2)	1.4(-18)	
1300	7.6(-2)	5.0(-19)	
1280	6.9(-3)	2.8(-19)	
1260	1.6(-2)	4.3(-19)	

*The solar fluxes are integrated over wavelength intervals whose center value is given. Note that the values in parentheses are the powers of 10 by which the primary tabular entry is to be multiplied.

Table 2: Schumann-Runge Band Coefficients (cgs units)¹.

Band	Wavelength (Å)	α_1	β_1	γ_1	δ_1
1	2025.0	8.2595(22)	6.9850(8)	1.1983(-23)	6.4880(-14)
2	2000.0	8.0106(22)	-3.5546(9)	1.2662(-23)	9.6723(-14)
3	1985.0	7.3112(22)	2.2040(9)	1.3033(-23)	3.0529(-13)
4	1971.8	1.8757(22)	1.0081(11)	1.2899(-23)	1.7876(-12)
5	1947.0	1.4252(22)	1.0586(11)	1.2204(-23)	2.6838(-12)
6	1924.0	1.2321(21)	2.5293(11)	1.4519(-23)	5.4926(-12)
7	1902.4	4.6314(20)	1.7798(11)	1.8859(-23)	8.3986(-12)
8	1882.2	1.4269(20)	1.3011(11)	1.5313(-23)	1.2232(-11)
9	1863.4	6.8431(19)	7.8005(10)	4.9293(-23)	1.9898(-11)
10	1846.2	5.9996(19)	4.6831(10)	7.7757(-23)	3.1147(-11)
11	1830.6	1.9521(19)	3.9664(10)	1.0391(-22)	3.5539(-11)
12	1816.4	7.2957(17)	3.1870(10)	2.1977(-22)	5.0541(-11)
13	1803.6	9.0621(18)	1.5782(10)	4.6920(-22)	9.0615(-11)
14	1792.6	1.2199(18)	2.4265(10)	1.1067(-21)	6.7403(-11)
15	1782.6	4.0394(18)	2.4928(10)	2.1219(-21)	6.1440(-11)
16	1774.6	8.2969(18)	1.1984(10)	3.0367(-21)	1.0362(-10)
17	1768.6	5.5205(18)	5.2439(9)	8.7466(-21)	1.8609(-10)
18	1763.2	5.0849(18)	2.5956(9)	2.1935(-20)	2.4514(-10)
19	1750.0	3.3967(18)	1.4959(9)	5.2699(-20)	3.1771(-10)

¹These coefficients were supplied by McConnell (1974).

Table 3: Model Atmosphere

Z(km)	T($^{\circ}$ K)	[O](cm^{-3})	[O ₂](cm^{-3})	[N ₂](cm^{-3})	[O ₃](cm^{-3})
15	216.6	3(6)	8.586(17)	3.191(18)	2(12)
20	216.6	1(7)	3.920(17)	1.457(18)	3.1(12)
25	221.7	5(7)	1.720(17)	6.391(17)	4.5(12)
30	230.7	2(8)	7.823(16)	2.908(17)	3.1(12)
35	241.5	3.5(8)	3.651(16)	1.357(17)	1.6(12)
40	255.3	1.5(9)	1.752(16)	6.513(16)	6.7(11)
45	267.7	3(9)	8.794(15)	3.269(16)	2.1(11)
50	271.6	9(9)	4.660(15)	1.732(16)	7(10)
55	263.9	2(10)	2.565(15)	9.535(15)	2.2(10)
60	249.3	2.5(10)	1.414(15)	5.255(15)	7(9)
65	232.7	2.3(10)	7.564(14)	2.812(15)	2.2(9)
70	216.2	2(10)	3.863(14)	1.436(15)	7(8)
75	205.0	4(10)	1.824(14)	6.792(14)	2(8)
80	195.0	6.2(10)	8.204(13)	3.104(14)	3.1(8)
85	185.1	1.4(11)	3.548(13)	1.365(14)	1.2(8)
90	183.8	1.66(11)	1.422(13)	5.585(13)	2.7(7)
95	190.3	1.91(11)	5.483(12)	2.218(13)	4.6(6)
100	203.5	4.150(11)	1.991(12)	8.710(12)	1.3(6)
105	228.0	4.436(11)	6.653(11)	3.597(12)	1.5(5)
110	265.5	3.228(11)	2.500(11)	1.585(12)	1.4(4)
115	317.1	2.148(11)	1.086(11)	7.447(11)	1.2(3)
120	380.6	1.422(11)	5.420(10)	3.793(11)	1.5(2)

Table 4: Conversion Factors for $^{\circ}\text{K day}^{-1}$ to $\text{ergs cm}^{-3} \text{sec}^{-1}$

<u>Z(km)</u>		<u>Z(km)</u>	
15	2.26(-2)	70	1.02(-5)
20	1.03(-2)	75	4.80(-6)
25	4.52(-3)	80	2.19(-6)
30	2.06(-3)	85	9.59(-7)
35	9.60(-4)	90	3.90(-7)
40	4.60(-4)	95	1.54(-7)
45	2.31(-4)	100	6.01(-8)
50	1.23(-4)	105	2.43(-8)
55	6.75(-5)	110	1.06(-8)
60	3.73(-5)	115	5.07(-9)
65	1.99(-5)	120	2.63(-9)

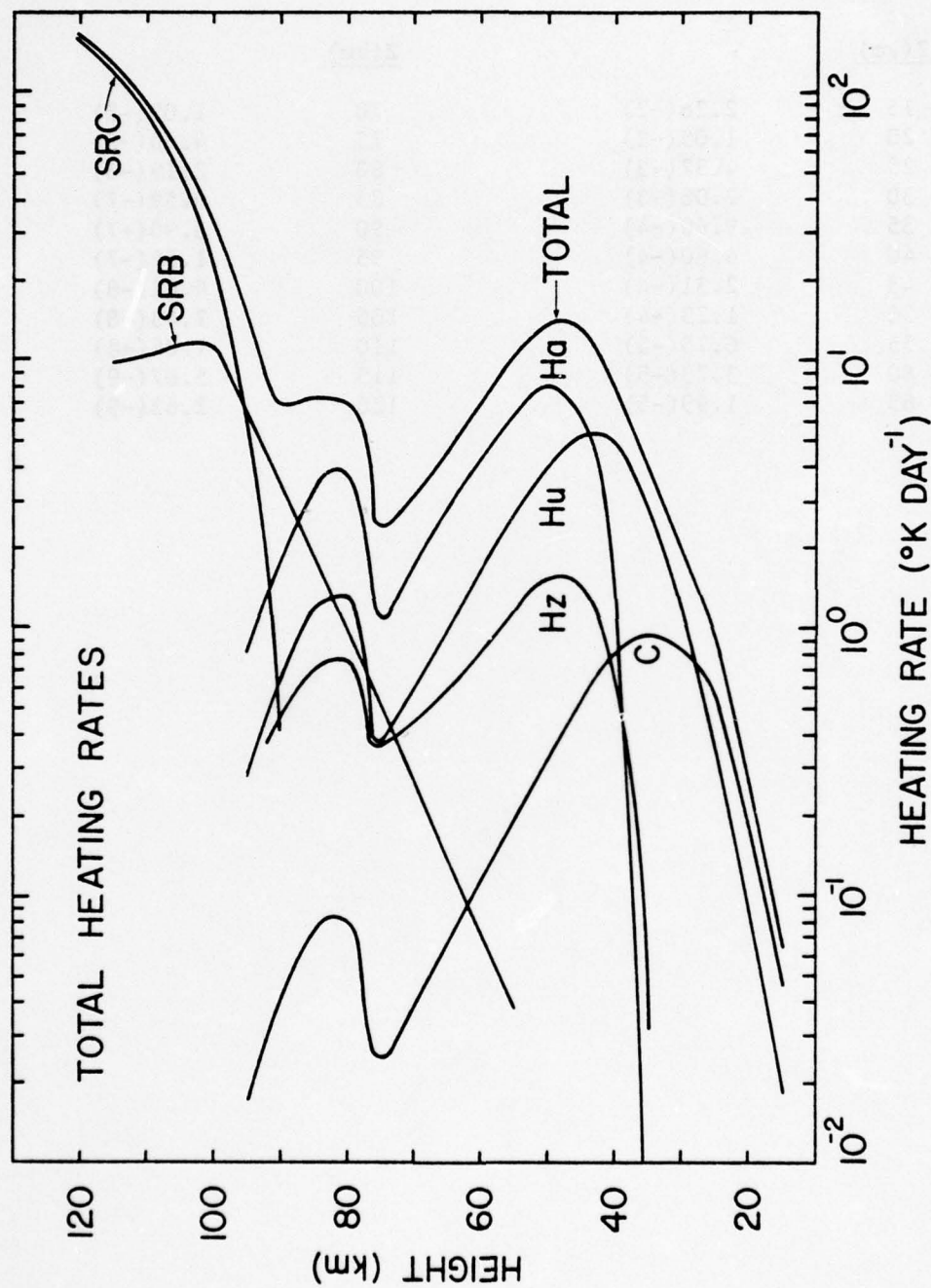


Fig. 1 — Diurnally-averaged total heating rates at the equator as a function of altitude in the Chappius (C), Huggins (Hu), Hartley (Ha), Herzberg (Hz), Schumann-Runge Bands (SRB), and Continuum (SRC) wavelength regions of the solar spectrum. Solar declination angle = 0°, equinox.

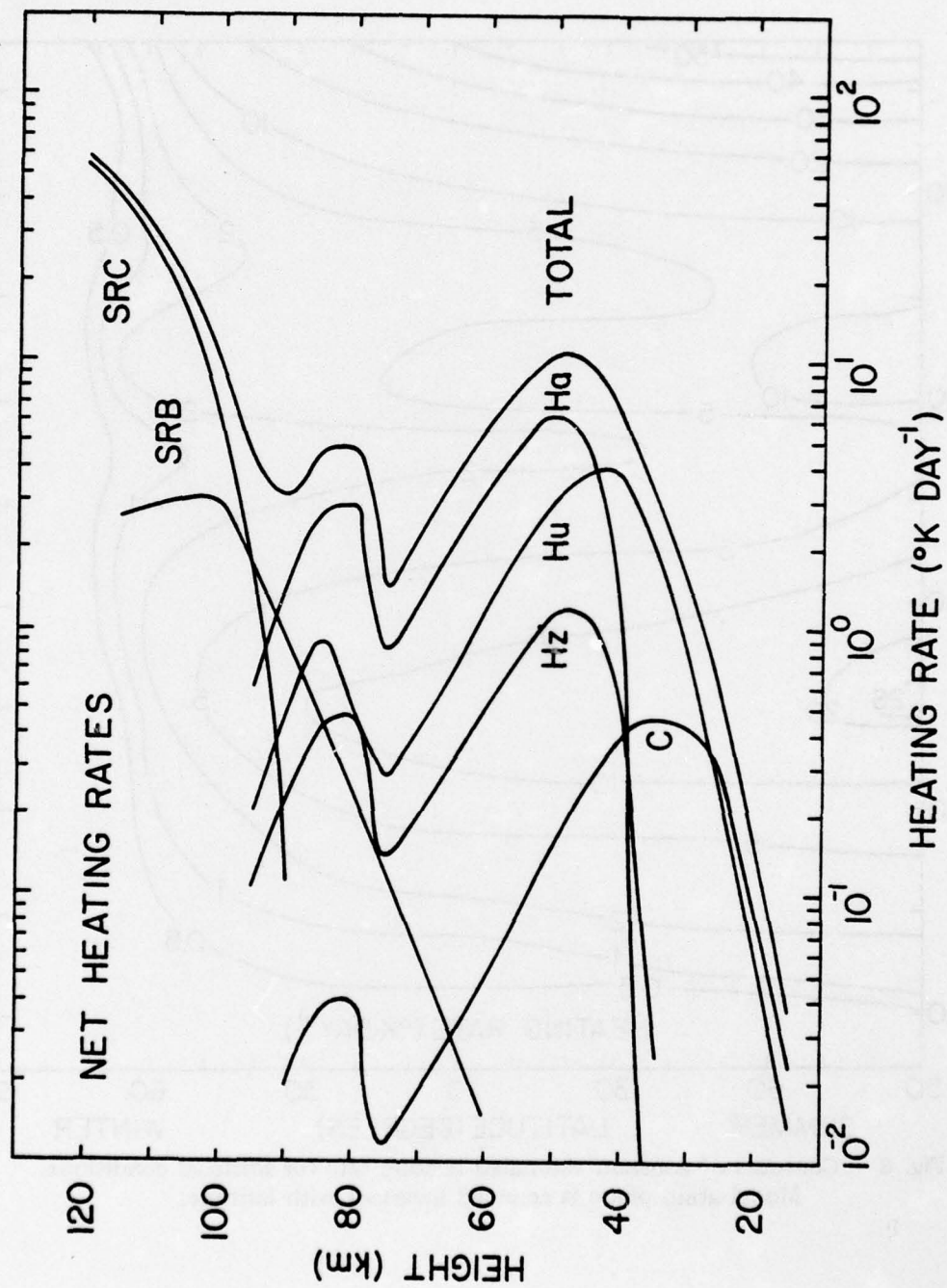


Fig. 2 — Same as Fig. 1, but for net heating rates

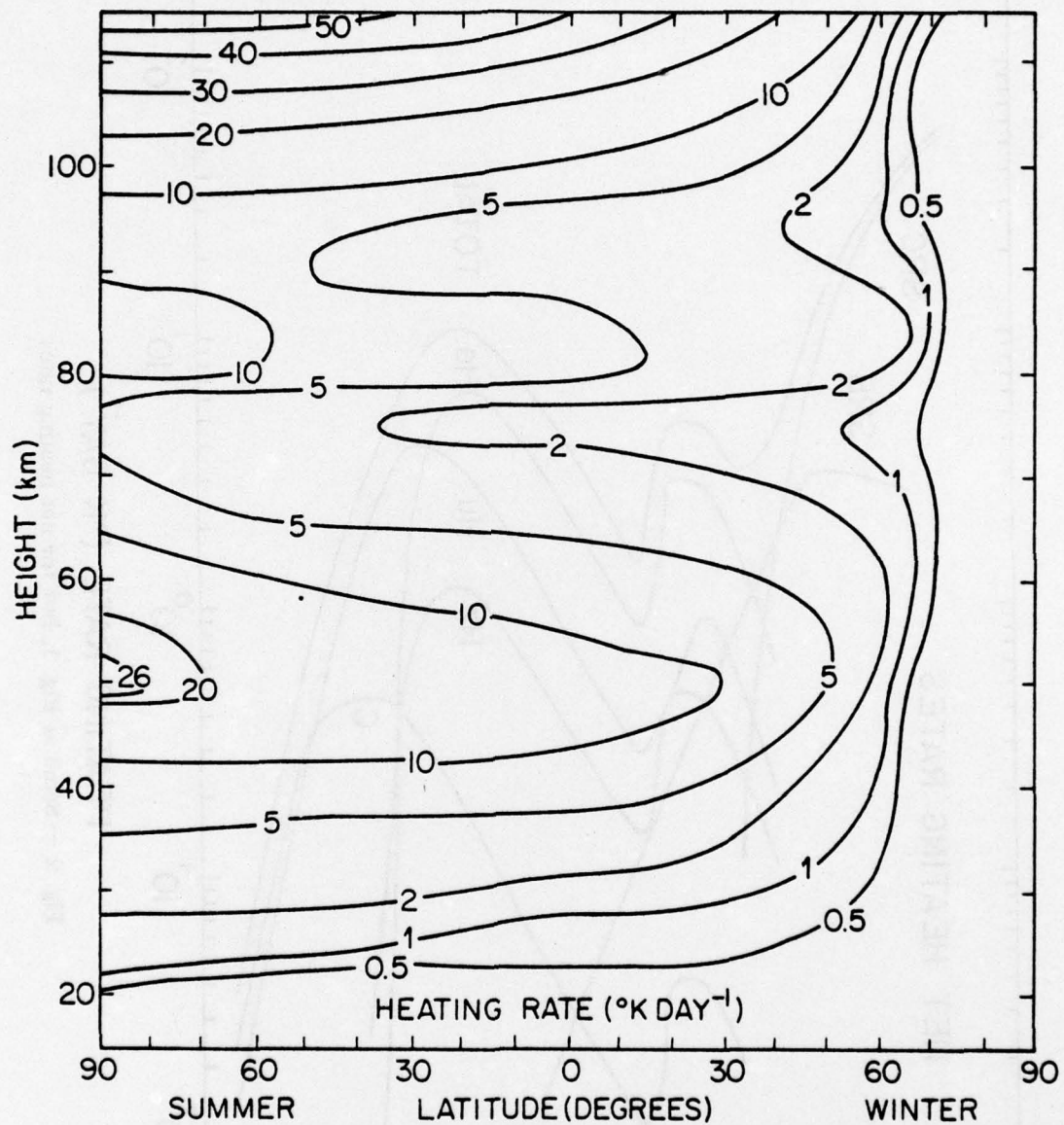


Fig. 3 — Contours of constant estimated heating rate for solstitial conditions.
Model atmosphere is assumed invariant with latitude.

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