PARAMETERIZATION OF THE ATMOSPHERIC HEATING RATE FROM 15 TO 120°C

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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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PARAMETERIZATION OF THE ATMOSPHERIC HEATING RATE FROM 15 TO 120 KM DUE TO \( \text{O}_3 \) AND \( \text{O}_4 \) ABSORPTION OF SOLAR RADIATION.

The atmospheric heating rate due to \( \text{O}_3 \) and \( \text{O}_4 \) absorption of solar radiation is parameterized with an accuracy of \( \pm 5 \) percent in the altitude region 15-120 km. For relevant wavelengths the effects of multiple scattering and ground reflection are also included. These parameterizations are computationally fast, efficient, and suitable for use in numerical models of atmospheric circulation.
## CONTENTS

- INTRODUCTION .................................................. 1
- EXACT HEATING RATE CALCULATION .......................... 2
- PARAMETERIZATION OF THE O$_3$ HEATING RATE .......... 4
- PARAMETERIZATION OF THE O$_2$ HEATING RATE .......... 8
- PARAMETERIZATION OF DIFFUSE SCATTERED SOLAR RADIATION ............................................... 12
- SUMMARY ......................................................... 16
- ACKNOWLEDGMENTS ................................................ 16
- REFERENCES ....................................................... 17
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 Å 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 Å). McConnell (1974) has noted that transmission of solar radiation in each band $i$, $T_r_i$, can be adequately represented by

$$T_{r_i} = \exp \left\{ -(\gamma_i N_2 + \delta_i N_2^2) \right\} \tag{1}$$

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

$$Q_{SRB}(O_2) = \sum_{i=1}^{19} F_i \sigma_i T_{r_i} [O_2] \tag{2}$$
where \( F_i \) is the solar flux integrated over each band, \([O_2]\) is the \( O_2 \) number density and the cross section \((\sigma_i)\) is given by

\[
\sigma_i^{-1} = \alpha_i + \beta_i N_2^{1/2}
\]

with \( \alpha_i \) and \( \beta_i \) 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 \((\varepsilon Q)\) defined as the energy absorbed minus the chemical energy stored by the dissociated products were computed with efficiency factors,

\[
\varepsilon_j = \left( \frac{hc}{\lambda_j} - D \right) \frac{hc}{\lambda_j}
\]

where \( D \) is the dissociation energy of the absorbing molecules (1.05 ev for \( O_3 \) and 5.12 ev for \( O_2 \)), \( \lambda_j \) is the wavelength of the photon, \( h \) is Planck's constant and \( c \) is the speed of light.
PARAMETERIZATION OF THE \( \text{O}_3 \) HEATING RATE

For the Chappius bands (c) we follow Lindzen and Will (1973) and write the \( \text{O}_3 \) heating rate \( (Q_c) \) as

\[
\frac{Q_c}{[\text{O}_3]} = F_c \sigma_c e^{-\sigma_c N_3}
\]

where \([\text{O}_3] \) is the \( \text{O}_3 \) number density and \( N_3 \) its column density along the solar radiation path. We find that

\[
F_c = 3.7 \times 10^5 \text{ ergs cm}^{-2} \text{ sec}^{-1}
\]

\[
\sigma_c = 2.85 \times 10^{-21} \text{ cm}^2
\]

gives the best fit to exact calculations of \( Q_c \). \( \sigma_c \) is 0.62 times the peak \( \text{O}_3 \) cross section at ~6000Å and \( F_c \) is 0.7 times the integrated flux over the Chappius bands. The net heating rate \( \varepsilon_c Q_c \) is obtained with \( \lambda_c = 6000\text{Å} \) for the efficiency factor \( \varepsilon_c \) from equation (4).

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

\[
\frac{Q_{\text{Ha}}}{[\text{O}_3]} = F_{\text{Ha}} \sigma_{\text{Ha}} e^{-\sigma_{\text{Ha}} N_3}
\]

where

\[
F_{\text{Ha}} = 5460 \text{ ergs cm}^{-2} \text{ sec}^{-1}
\]

\[
\sigma_{\text{Ha}} = 8.8 \times 10^{-18} \text{ cm}^2
\]
with $\sigma_{\text{Ha}}$ equal to 0.8 times the peak $O_3$ cross section at $\lambda = 2525 \text{ Å}$ and $F_{\text{Ha}}$ the integrated flux over the 2425–2775 Å interval. The net heating rate $\varepsilon_{\text{Ha}O_3}$ is calculated with $\lambda_j = 2500 \text{ Å}$ in equation (4).

In the Huggins bands (Hu, defined here as the 2775–3600 Å interval) we assume, as Lindzen and Will (1973), that the $O_3$ cross section has an exponential variation

$$\sigma = \sigma_{\text{Hu}} e^{-\lambda \lambda_{-1}}.$$  \hspace{1cm} (9)

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

$$\frac{Q_{\text{Hu}}}{[O_3]} = \int_{\lambda_{\text{short}}}^{3600 \lambda} I_1 \sigma e^{-\sigma N \lambda_{3} d\lambda} + \int_{\lambda_{\text{long}}}^{\lambda_{\text{long}}} I_2 \sigma e^{-\sigma N \lambda_{3} d\lambda}$$

or

$$\frac{Q_{\text{Hu}}}{[O_3]} = \frac{1}{MN_3} \left[ I_1 + (I_2 - I_1) \exp \left[ -\sigma_{\text{Hu}N \lambda_{3} e^{-\lambda_{\text{long}}} \lambda_{-1}} \right] - I_2 \exp \left[ -\sigma_{\text{Hu}N \lambda_{3} e^{-\lambda_{\text{short}}} \lambda_{-1}} \right] \right]$$ \hspace{1cm} (10)

where the atmosphere is optically thin at 3600 Å. Numerically, an excellent fit to the exact heating rate is obtained with

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

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

$$M = 0.0127 \text{ Å}^{-1}$$

$$\lambda_{\text{short}} = 2805 \text{ Å}$$
\[
\lambda_{\text{long}} = 3055 \ \text{Å}
\]
\[
\sigma_{\text{Hu}} = 0.0125 \text{ cm}^2.
\]

The intensities \(I_1\) and \(I_2\) can be related to fluxes integrated over the respective wavelength intervals. \(\Delta \lambda_1 = 3600 - \lambda_{\text{long}} = 3450\) Å and 
\[\Delta \lambda_2 = \lambda_{\text{long}} - \lambda_{\text{short}} = 2500\] Å. 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 interval 2775–3055 Å 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 Å) 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 \((Q_{\text{Hz}})\) can be obtained with

\[
Q_{\text{Hz}} = F_{\text{Hz}} \left\{ \sigma_{\text{Hz}}(O_2)[O_2] + \sigma_{\text{Hz}}(O_3)[O_3] \right\} \exp \left[ -\sigma_{\text{Hz}}(O_2) N_2 \right.
- \sigma_{\text{Hz}}(O_3) N_3 \right] \] (12)

and

\[
F_{\text{Hz}} = 1.5 \times 10^3 \text{ ergs cm}^{-2} \text{ sec}^{-1}
\]
\[
\sigma_{\text{Hz}}(O_2) = 6.6 \times 10^{-24} \text{ cm}^2
\]
\[
\sigma_{\text{Hz}}(O_3) = 4.9 \times 10^{-18} \text{ cm}^2
\]
\[
\lambda_j = 2290 \text{ Å to calculate } \sigma_{\text{Hz}}
\]

where \(F_{\text{Hz}}\) 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
\( \text{O}_3 \) 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 \( \text{O}_3 \text{ day}^{-1} \) to ergs cm\(^{-3}\) sec\(^{-1}\) are
given in Table 4.

Above 45 km \( \text{O}_3 \) absorption in the Hartley region is the dominant
heat source, whereas below 28 km the Chappuis band absorption is
dominant. In the intermediate region the Huggins bands dominate.
The secondary peak in the heating rate at \( \approx 85 \) km corresponds to the
secondary maximum in the \( \text{O}_3 \) concentration in the model atmosphere.
Thus, thermodynamically, this \( [\text{O}_3] \) 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 \( \sim 10^{-17} \text{ cm}^2 \), and 1520–1750Å where the O₂ cross section is proportional to \( e^{-\lambda} \). For the 1250–1520Å region we may approximate the heating as

\[
\frac{Q_{\text{SRC}}}{[O_2]} = F_{\text{SRC}} \sigma_{\text{SRC}} e^{-\sigma_{\text{SRC}} N_2}
\]

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 \( F_{\text{SRC}} \) is the integrated flux over this wavelength region and \( \sigma_{\text{SRC}} \) is the average cross section. For the 1520–1750Å region we divide it into two intervals with \( \sigma(O_2) \sim e^{-\lambda} \) and obtain a total heating rate of

\[
\frac{Q_{\text{SRC}}}{[O_2]} = \frac{1}{N_2} \left\{ \frac{I_N}{M} e^{-\sigma_N N_2} + \frac{I_s - I_N}{M} e^{-\sigma_m N_2} - \frac{I_s}{M} e^{-\sigma_s N_2} \right\}
\]

where \( I_N \) denotes long wavelength end of spectrum, \( I_s \) denotes short wavelength end and \( \sigma_m \) denotes O₂ cross section at the junction of these intervals (\( \sim 1660Å \)). The following values were found to give an excellent fit.
\[
\frac{I_L}{M} = 3.43 \text{ ergs cm}^{-2} \text{sec}^{-1}
\]
\[
\frac{I_S}{M} = 1.35 \text{ ergs cm}^{-2} \text{sec}^{-1}
\]
\[
\sigma_L = 2.9 \times 10^{-19} \text{ cm}^2
\]
\[
\sigma_m = 1.54 \times 10^{-18} \text{ cm}^2
\]
\[
\sigma_s = 1.1 \times 10^{-17} \text{ cm}^2
\]

\(I_L\) is approximately 0.6 times the integrated solar flux in the 1660-1750\AA\ interval, while \(I_S\) is approximately 0.5 times the solar flux in the 1520-1660\AA\ interval. The \(O_2\) cross sections \(\sigma_L\), \(\sigma_m\), and \(\sigma_s\) are approximately the values at 1750, 1660, and 1520\AA, respectively. To compute the net heating rate we recommend

\[
\frac{\varepsilon I_L}{M} = 0.98 \text{ ergs cm}^{-2} \text{sec}^{-1}
\]
\[
\frac{\varepsilon I_S}{M} = 0.43 \text{ ergs cm}^{-2} \text{sec}^{-1}
\]
\[
\sigma_L = 2.9 \times 10^{-19} \text{ cm}^2
\]
\[
\sigma_m = 1.7 \times 10^{-18} \text{ cm}^2
\]
\[
\sigma_s = 1.15 \times 10^{-17} \text{ cm}^2
\]

where \(\varepsilon \approx 0.3\).

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 \(\pm 20\) percent in this parameterization. The following expression represents the total
heating rate in the 60–100 km region

\[ \frac{Q_{SRB}}{[O_2]} = \frac{1}{aN_2 + bN_2^{1/2}} \]  

(17)

where

\[ a = 0.143 \text{ cgs units} \]

\[ b = 9.64 \times 10^8 \text{ cgs units} \]

(18)

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

\[ \frac{Q_{SRB}}{[O_2]} = 9.03 \times 10^{-9} \text{ ergs sec}^{-1} \]  

(19)

For the net heating rate we obtain

\[ a = 0.67 \text{ cgs units} \]

\[ b = 3.44 \times 10^9 \text{ cgs units} \]

(20)

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

\[ \frac{Q_{SRB}}{[O_2]} = 2.43 \times 10^{-19} \text{ ergs sec}^{-1} \]  

(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 \( \text{O}_3 \) concentration there.

The overall accuracy of the parameterized heating rates is \( \pm 5 \) percent over the altitude region 15-120 km. Below approximately 80 km the \( \text{O}(\text{3P}) \) formed by \( \text{O}_3 \) and \( \text{O}_2 \) dissociation recombines quickly, and the actual heating rate of the atmosphere is the total photon energy absorbed. Above 80 km the \( \text{O}(\text{3P}) \) produced by \( \text{O}_3 \) and \( \text{O}_2 \) dissociation may be transported significantly in the vertical direction before recombining, and the actual heating rate is the net heating rate (\( \epsilon Q \)) plus the chemical energy released by locally recombining \( \text{O}(\text{3P}) \). To a good first approximation we can estimate the actual heating rate by summing the total \( \text{O}_3 \) heating rate and the net \( \text{O}_2 \) 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 3000Å 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 O₃ absorption region on top of a reflecting layer with an effective albedo \( \omega_o \) that depends on the ground reflectivity \( R_g \) and lower atmosphere albedo \( R_a \) as follows:

\[
\omega_o = R_a + [1 - R_a] \frac{0.856 R_g}{1 - 0.144 R_g} \tag{22}
\]

Let the vertical optical depth due to O₃ absorption be

\[
\tau^* = \int_0^\infty n \sigma dz \tag{23}
\]

where \( n \) is the O₃ number density, \( \sigma \) is its cross section, \( z \) is height, and \( d\tau = -n \sigma dz \). With \( \theta \) 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

\[
F = \int_{-1}^1 I \mu d\mu = \int_0^1 I^+ \mu d\mu + \int_{-1}^0 I^- \mu d\mu \tag{24}
\]
and the corresponding heating rate is

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

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

\[ \mu \frac{dI}{d\tau} = I \] (26)

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

\[ I = I_0 e^{\mu} . \] (27)

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

\[ I^-(\tau = 0, \mu) = F_\Theta \delta(\mu + \mu_0) \] (28)

where \( F_\Theta \) is the downward directed solar flux with direction \( \mu_0 \). Thus

\[ I^-(\tau, \mu) = F_\Theta \delta(\mu + \mu_0) e^{\mu}, \mu < 0 . \] (29)

For the upward intensity component the boundary condition is applied at the reflecting surface (\( \tau = \tau^* \)) and is a Lambert surface with albedo \( \omega_0 \),

\[ I^+(\tau^*, \mu) \text{ is isotropic} \]

\[ F^+ = \omega_0 F^- \text{ at } \tau = \tau^* . \] (30)
Then at $\tau^*$

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

or with equation (24)

$$I^+(\tau^*, \mu) = 2\omega_0^2 \mu_0 \frac{\mu}{\mu_0}$$

and

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

(32)

Since $d\tau = -\sigma dz$, 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

$$Q = F_0 e^{-\sigma n} + 2\omega_0^2 \mu_0 \frac{\mu}{\mu_0} E_2 (\tau^* - \tau) \sigma n$$

(33)

where the exponential integral $E_2$

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

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

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

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

$$Q = F_0 \sigma n \left\{ e^{\frac{-\tau}{\mu_0}} + 2w_0 \mu_0 e^{\frac{-\tau^*}{\mu_0}} e^{-1.9(\tau^* - \tau)} \right\}$$

(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 3000-4000Å solar uv radiation.
SUMMARY

The atmospheric heating rates due to $\text{O}_2$ and $\text{O}_3$ absorption of solar radiation have been successfully parameterized with an accuracy of $\pm$ 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.

ACKNOWLEDGMENTS

I would like to thank J. C. McConnell for communicating the Schumann-Runge Band Coefficients in Table 2 used to generate the "exact" heating rate calculation. This research was supported by the Naval Air Systems Command.
REFERENCES


McConnell, J. C., Private communication, 1974.

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*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)

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1. These coefficients were supplied by McConnell (1974).
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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. 3 — Contours of constant estimated heating rate for solstitial conditions. Model atmosphere is assumed invariant with latitude.
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