Oxygen and Carbon Monoxide Cooling

in Planetary Thermospheres

Richard W. Stewart

Institute for Space Studies
Goddard Space Flight Center, NASA
New York, N. Y.

ABSTRACT

A study of the effectiveness of atomic oxygen and carbon monoxide as cooling agents in a planetary thermosphere is carried out. Analytic expressions for the total flux radiated by these constituents are derived based on the assumption of a sharply defined radiation zone in which the scale height variation is linear. It is found that the total flux radiated by atomic oxygen can exceed that radiated by carbon monoxide if the temperature in the radiating region is less than $300^{O}K$.

The time-dependent thermal conduction equation is considered briefly. It is shown that the cooling time for carbon monoxide is of the order of a few hours, in contrast to the several-day cooling time of atomic oxygen. A substantial overnight cooling is thus to be expected in planetary thermospheres which contain carbon monoxide.

1. Introduction

Atomic oxygen and carbon monoxide are present in varying degree in the upper atmospheres of the Earth, Mars and Venus. The Earth's thermosphere is predominately atomic oxygen and does not contain much carbon monoxide. The atmospheres of Mars and Venus, on the other hand, contain substantial CO_2 and must therefore contain an abundance of both of the dissociation products, CO and O.

Each of these constituents can cool a planetary thermosphere by infrared emission of some of the thermal energy deposited by solar extreme ultraviolet (EUV) radiation. The possible importance of the magnetic dipole transition $O(^3P_1) \rightarrow O(^3P_2)$ within the ground state triplet of oxygen in cooling the Earth's thermosphere was pointed out by Bates (1951). McElroy et al. (1965) have studied the effectiveness of CO rotational transitions in cooling the Martian thermosphere.

The power radiated by atomic oxygen is only weakly temperature dependent, whereas the power radiated by carbon monoxide is proportional to the square of the temperature. However, direct comparison of the power

radiated by each constituent can be misleading. The physically significant quantity is the total energy loss per cm^2 column of atmosphere by each constituent. The calculations presented below show that the total energy loss by O and CO is more strongly temperature dependent than is the power radiated locally. The importance of the 62_u radiation of atomic oxygen relative to rotational loss by CO is significantly greater than could be inferred solely from comparison of the power radiated by each constituent. If the temperature at the altitudes where radiative loss occurs is less than $300^{\circ}K$, atomic oxygen can be the dominant radiator. A precise determination depends on the scale height gradients in the radiation zone, the temperatures at which radiative loss commences (assuming it commences at a well-defined optical depth in each constituent), and whether or not the constituents are in diffusive equilibrium. Even for temperatures in the radiation zone of $\sim 500^{\circ}K$ the ratio of O/CO energy loss may be $\sim.5$.

The analytic expressions developed in this paper for the flux radiated by O and CO may serve as a useful check on the results of detailed integrations of the thermal

conduction equation.

The time-dependent form of the thermal conduction equation is considered with a view to obtaining a qualitative idea of the amplitude of the temperature drop expected during the night. When the terms representing conductive loss and radiative loss due to atomic oxygen are dropped, a simple expression for the temperature decay may be obtained. A cooling time for CO radiation is defined as the time in which the temperature would fall to half its initial value due to CO radiative loss alone. This cooling time is found to vary from about 7 hours for an initial temperature of 1000°K to 12 hours for an initial temperature of 600°K. In the absence of a nocturnal heat source, CO cooling alone will cause the exospheric temperature to fall to $\leqslant 300^{\circ}$K in a 12 hour period for initial temperatures $\leqslant 1000^{\circ}$K.

2. Power Radiated Locally by O and CO

Radiative loss via transitions within the ground state triplet of atomic oxygen were considered by Bates (1951) in conjunction with his discussion of heating of the Earth's upper atmosphere. The ground state of atomic oxygen is an inverted triplet with the $^3P_0$ and $^3P_1$

levels lying .028 and .020 e.v. respectively above the $^3P_2$ level. The Einstein coefficients for these transitions are $A_{02} = 1.7 \times 10^{-5}$ sec^{-1} and $A_{12} = 8.9 \times 10^{-5}$ sec^{-1}. Due to the greater excitation energy of the $^3P_0$ level, the small statistical weight, $g_0 = 1$, and the relative magnitudes of the Einstein coefficients, emission from $^3P_0$ will be much smaller than that from $^3P_1$ and may be neglected. The question of thermodynamic equilibrium within the $O(^3P_{0,1,2})$ triplet was considered by Bates, who concluded that collisional excitation of the excited levels would probably occur much faster than photon emission if the total particle density were $\gtrsim 10^9$ cm^{-3}. It will be shown below that infrared emission in the 62μ oxygen line is almost certain to be effective at much higher densities and that the assumption of equilibrium within the oxygen ground state is therefore justified. With this assumption the power radiated in the 62μ line is

$$R_s = \epsilon_1 A_{12} n(O|^3P_1) = \epsilon_1 A_{12} n(O|^3P_{0,1,2}) \frac{g_1 e^{-\epsilon_1/kT}}{g_2 + g_1 e^{-\epsilon_1/kT} + g_0 e^{-\epsilon_0/kT}} \tag{1}$$

where ε_1 and ε_0 are the energies of the $^3P_1$ and $^3P_0$ levels, g_0, g_1, and g_2 are the statistical weights (the subscript refers to the corresponding J value) and n refers to the oxygen number densities. Evaluating the constants results in

$$R_s = 2.85 \times 10^{-18} \, n_{OX}(z) \, f(T) \; ergs/cm^3 sec \qquad (2)$$

where $n_{OX}(z)$ is the total oxygen density and

$$f(T) = \frac{3e^{-228/T}}{5 + 3e^{-228/T} + e^{-325/T}} \qquad (3)$$

The temperature dependence of the power radiated locally by atomic oxygen is not very great. The factor f(T) varies from 0 to 1/3 as T varies from 0 to ∞.

The expression for the power radiated locally by CO was also given by Bates. The power radiated is proportional to the square of the temperature in this case and is given by

$$R_r = 2.58 \times 10^{-23} \, n_{CO} \, T^2 \; ergs/cm^3 sec \qquad (4)$$

Rotational states are readily populated by collisions
(Zener, 1931) and it is highly probable that carbon
monoxide is in rotational equilibrium well above the
region of radiative loss.

3. Equation of Radiative Transfer for a Doppler-Broadened Line

An accurate evaluation of the total energy lost by
a radiating constituent such as O or CO requires a deter-
mination of the altitude at which unit optical depth
occurs. We will assume that radiative loss is fully
effective above unit optical depth and ineffective at
lower altitudes. An expression for the optical depth in
Doppler-broadened lines may be obtained from the equation
of radiative transfer. We consider a two-level system
with the upper energy state denoted by subscript 2 and
the lower state by subscript 1, and a radiation field of
density ρ_ν. The rate of decrease in the population of
the upper energy state is

$$- \frac{dn_2}{dt} = n_2 A_{21} + n_2 B_{21} \rho_\nu - n_1 B_{12} \rho_\nu \tag{5}$$

where A_{21}, B_{21}, and B_{12} are the Einstein coefficients for

spontaneous and induced emission and for absorption.
Each transition resulting in a decrease in n_2 corresponds
to the addition of a photon to the radiation field. Since
this emission occurs over a frequency range the decrease
in n_2 corresponds to an increase in the photon intensity
(in units cm^{-2} steradian^{-1} sec^{-1} (cps)$^{-1}$) integrated over
frequency and direction, i.e.,

$$-\frac{dn_2}{dt} = \int d\Omega \, \frac{d}{ds} \int_0^\infty d\nu \, I_\nu \tag{6}$$

where $d\Omega$ is the element of solid angle, I_ν the radiation
intensity, and ds an element of path length in the medium.
If the spectral line due to transitions between states
2 and 1 is Doppler-broadened we may write

$$\int_0^\infty I_\nu d\nu = \int_0^\infty I_{\nu_0} e^{-\lceil (\nu-\nu_0)/\alpha_D \rceil^2} d(\nu-\nu_0) = \frac{\sqrt{\pi}}{2} \alpha_D I_{\nu_0} \tag{7}$$

where α_D is the Doppler width and I_{ν_0} the intensity at the
line center. We now make use of the relationship between
the radiation density and intensity,

$$\rho_\nu = \frac{1}{c} \int I_\nu d\Omega = \frac{4\pi}{c} \bar{I}_\nu \tag{8}$$

between the Einstein coefficients

$$\frac{B_{21}}{A_{21}} = \frac{c}{8\pi}\left[\frac{c}{\nu}\right]^2 = \delta_\nu \qquad \text{and} \qquad \frac{B_{12}}{B_{21}} = \frac{g_2}{g_1} \qquad (9)$$

where g_2 and g_1 are the statistical weights of levels 2 and 1, and substitute the combined results of (6) and (7) in (5) to obtain the radiative transfer equation

$$\frac{1}{4}\frac{dF_\nu}{dz} = \frac{1}{2\pi^{3/2}}\frac{A_{21}}{\alpha_D} n_2\left[1 + \frac{4\pi\delta_\nu}{c}(1 - \frac{g_2}{g_1}\frac{n_1}{n_2})\,\bar{I}_\nu\right] \qquad (10)$$

where $F_\nu = \frac{1}{\pi}\int\mu I_\nu d\Omega$ is the photon flux. The subscript 0 on ν has been dropped. The relation between the directions specified by z and s is dz = ds cos θ where θ is the angle between directions z and s. If we now assume that the levels are in thermal equilibrium we have

$$\frac{n_1}{n_2} = \frac{g_1}{g_2} e^{\epsilon_{21}/kT} \qquad \text{and} \qquad n_2 = \frac{g_2}{Z(T)} e^{-\epsilon_2/kT} n \qquad (11)$$

where $\epsilon_{21} = \epsilon_2 - \epsilon_1$ is the energy difference between states 2 and 1, n is the total number density and Z(T) is the partition function for the system. With the use of (11) the radiative transfer equation is

$$\frac{1}{4}\frac{dF_\nu}{dz} = -\sigma_D n \bar{I}_\nu + \epsilon_D n \qquad (12)$$

where

$$\sigma_D = \frac{1}{4\pi^{3/2}} \frac{g_2 A_{21}}{Z(T)} \left[\frac{m}{2kT}\right]^{1/2} \left[\frac{c}{\nu}\right]^3 e^{-\epsilon_1/kT} \left[1 - e^{-\epsilon_{21}/kT}\right] \tag{13}$$

is the absorption cross section in the line and

$$\epsilon_D = \frac{1}{2\pi^{3/2}} \frac{g_2 A_{21}}{Z(T)} \left[\frac{m}{2kT}\right]^{1/2} \left[\frac{c}{\nu}\right] e^{-\epsilon_2/kT} \tag{14}$$

is the emission coefficient. The subscript D refers to the fact that these expressions hold for Doppler-broadened lines. The ratio ϵ_D/σ_D is just the Plank distribution (for photons) as it must be since thermal equilibrium has been assumed.

4. Optical Depths in O and CO

We will obtain some initial estimates of the over-lying number densities in oxygen and carbon monoxide at which these constituents may begin to cool a planetary thermosphere by radiative loss. The optical depth in a line is defined by

$$d\tau = -\sigma_D n\, dz \tag{15}$$

where the altitude variable is denoted by z. If the con-stituent n is distributed in diffusive equilibrium in an isothermal atmosphere, the optical depth is

$$\tau = \sigma_D \, n \, H \tag{16}$$

and this unit optical depth occurs at an altitude where the overlying number density is

$$n \, H = \frac{1}{\sigma_D} \tag{17}$$

For the 62μ line we evaluate the constants in (13) and use the partition function appropriate to the $O(^3P_{0,1,2})$ triplet to find

$$\sigma_D(O) = 8.9 \times 10^{-16} \frac{1 - e^{-228/T}}{5 + 3e^{-228/T} + e^{-325/T}} \frac{1}{T^{1/2}} \, cm^2 \tag{18}$$

If we take T = 300°K as an estimate of the isothermal temperature, then the overlying oxygen number density at unit optical depth is

$$n_{OX} \, H_{OX}|_{\tau=1} = 2.4 \times 10^{17} \, cm^{-2} \tag{19}$$

We recall that the initial assumption of thermal equilibrium in the ground state oxygen triplet required total number densities $\gtrsim 10^9$. That radiative cooling commences below the altitude at which departures from equilibrium occur is obvious from (19) since atomic oxygen number densities of 10^9 would correspond to unit optical depth in the 62μ line only if the scale height were ≈ 1000 km.

In the case of carbon monoxide we have transitions between rotational states $J \rightleftarrows J-1$ for all values of the angular momentum quantum number J. We will assume, as has been done by McElroy et al. (1965), that the optical depth in the carbon monoxide rotational lines is given by the optical depth in the line in which most energy is transferred. The rotational state with the greatest occupation is specified by

$$J_{MAX} = \left[\frac{T}{2\theta_r} \right]^{1/2} \tag{20}$$

The Einstein coefficient for spontaneous emission in this line may be evaluated from the general expression for the A coefficient (Schiff, 1955, Chapter 10) using the dipole

matrix element for adjacent states of a rigid rotator.

We have

$$A_{J,J-1} = \frac{4}{3\hbar}(4\pi B)^3 d^2 \frac{J^4}{2J+1}$$

(21)

where B is the rotational constant of the molecule, d the dipole moment of CO and $\hbar$ Plank's constant. Evaluating this and all other J-dependent terms in (13) at $J = J_{MAX}$ gives the absorption cross section in the strongest rotational line as

$$\sigma_D(CO) = \frac{4\pi^{3/2}}{3\sqrt{e}} \frac{d^2}{\hbar} \left[\frac{m}{kT}\right]^{1/2} \left[\frac{\theta_r}{T}\right]^{1/2} \left[1-e^{-(2\theta_r/T)^{1/2}}\right]$$

(22)

where θ_r is the characteristic rotational temperature hcB/k. Evaluating the constants, with d = .12 x 10^{-18} (Fowler, 1935), B = 1.93 cm^{-1} (Bates, 1951), and expanding the exponential to first order we find

$$\sigma_D(CO) = \frac{1.35 \times 10^{-13}}{T^{3/2}} \ cm^2$$

(23)

This expression was given by McElroy et al. (1965). At a temperature T = 300°K unit optical depth in the CO

rotational lines thus occurs at an overlying CO density
of

$$n_{CO} \; H_{CO} \big|_{\tau=1} = \frac{1}{\sigma_D(CO)} = 3.8 \times 10^{16} \; cm^{-2} \qquad (24)$$

Equations (19) and (24) show clearly that conclusions as
to the relative effectiveness of O and CO as cooling
agents based on a direct comparison of the power radiated
locally is misleading. The sum of the oscillator strengths
for the CO rotational lines is greater than the oscillator
strength of the 62μ O emission. However, this implies
not only that CO is a more effective emitter in the infra-
red than is O, but is also a more effective absorber.
Only a consideration of the balance between emission and
loss can lead to valid conclusions regarding the relative
effectiveness of these constituents as radiators.

5. Comparison of Total Fluxes Radiated by O and CO

We will now assume that in the altitude region
from which radiative loss occurs the scale height may
be adequately described in terms of a linear variation
i.e.,

$$H(z) = H_0 + \beta z \tag{25}$$

where H_0 is the scale height at the bottom of the zone
and β is the (constant) scale height gradient. The
number density of a constituent is given in this case by

$$n(z) = \frac{n_0 T_0}{T(z)} \left[\frac{H_0}{H} \right]^{1/\beta} \tag{26}$$

The subscript 0 on a quantity refers to the value of
that quantity at the altitude of the bottom of the radia-
tion zone, i.e., at unit optical depth. This altitude
is different for different constituents, but this dis-
tinction need not be made yet. The optical depth in a
given constituent is

$$\tau(z_0) = -\int_{z_0}^{z_1} n(z)\, \sigma_D(T)\, dz \tag{27}$$

where we assume that z_1 denotes the altitude of the top
of the radiating zone and that contributions to the opti-
cal depth from greater altitudes are negligible. The
altitude z_1 is not strictly defined, but should be
chosen at least one scale height above z_0. Using (18)

and (23) for the absorption cross sections in O and CO
we find the following expressions for the optical depths
in these constituents

$$\tau(O) = \frac{\sigma_{D_0}(O)}{1+\beta_{OX}/2} (n_0 H_0)_{OX} \left[1 - \Lambda_{OX}^{(2+\beta_{OX})/2\beta_{OX}} \right] \tag{28}$$

$$\tau(CO) = \frac{\sigma_{D_0}(CO)}{1 + \frac{3}{2}\beta_{CO}} (n_0 H_0)_{CO} \left[1 - \Lambda_{CO}^{(2+3\beta_{CO})/2\beta_{CO}} \right] \tag{29}$$

where $\Lambda = T_0/T_1$ is the ratio of temperatures at the
bottom and top of the radiation zone. Subscripts OX and
CO have been appended to quantities which refer to
atomic oxygen and carbon monoxide. In the derivation of
(28) from (27) only the $T^{-1/2}$ dependence of $\sigma_D(T)$ was
explicitly included in the integration. The remaining
temperature-dependent term in (18), which varies from 0
to 1/5 as T varies from ∞ to 0, is assumed evaluated at
T_0. This approximation will slightly overestimate the
optical depth at 62μ (for a given altitude) and corre--
spondingly underestimate the effectiveness of O cooling.
The total flux radiated by a constituent is given by

$$F_R = \int_{z_0}^{z_1} R(z,T) \, dz \tag{30}$$

where $R(z,T)$ is the power radiated. Using (2) and (4) for the power radiated by O and CO we find

$$F_R(O) = 2.8 \times 10^{-18} (n_0 H_0)_{OX} f(T_0) \left[1 - \Lambda_{OX}^{1/\beta_{OX}} \right] \qquad (31)$$

$$F_R(CO) = \frac{2.58 \times 10^{-23} (n_0 T_0^2 H_0)_{CO}}{1 - 2\beta_{CO}} \left[1 - \Lambda_{CO}^{(1-2\beta_{CO})/\beta_{CO}} \right] \qquad (32)$$

The function $f(T_0)$ appearing in (31) and given explicitly by (3) was not included in the integrand of (30) but is assumed evaluated at T_0. The variation of $f(T)$ with T is relatively slow for $T > 250^{O}K$. The expression (32) was given by McElroy et al. (1965). If we now evaluate the product nH appearing in (31) and (32) at unit optical depth (using (28) and (29)) we obtain the total energy loss by O and CO in a planetary thermosphere (in ergs/ cm^2 sec)

$$F_R(O) = 9.6 \times 10^{-3} (1 + \frac{\beta_{OX}}{2}) E(T_0) T_0^{1/2} \left[\frac{1 - \Lambda_{OX}^{1/\beta_{OX}}}{1 - \Lambda^{(2+\beta_{OX})/2\beta_{OX}}} \right] \qquad (33)$$

$$F_R(CO) = 9.5 \times 10^{-11} \frac{2+3\beta_{CO}}{1-2\beta_{CO}} T_0^{7/2} \left[\frac{1 - \Lambda_{CO}^{(1-2\beta_{CO})/\beta_{CO}}}{1 - \Lambda_{CO}^{(2+3\beta_{CO})/2\beta_{CO}}} \right] \qquad (34)$$

where

$$E(T_0) = \frac{1}{e^{228/T_0} - 1}$$ (35)

It must be borne in mind that T_0 may refer to different temperatures in the expressions relating to O and CO. For temperatures $T_0 \gtrsim 300°K$ the flux lost in the 62μ line is roughly proportional to $T_0^{3/2}$ since $E(T_0) \approx T_0$. The presence of atomic oxygen in a planetary thermosphere therefore does, to some extent, act as a thermostat since the total energy loss increases more rapidly than the temperature. In an atmosphere containing both O and CO the thermostatic effect of CO will of course predominate since the energy loss by CO goes as $T_0^{7/2}$.

We will neglect the difference in temperatures at unit optical depths in O and CO and denote by T_R a mean temperature in the altitude region between which O and CO begin to radiate. The ratio of the total heat fluxes radiated by O and CO is then

$$R = \frac{F_R(O)}{F_R(CO)} = 5 \times 10^7 \frac{(2+\beta_{OX})(1-2\beta_{CO})}{(2+3\beta_{CO})} \frac{E(T_R)}{T_R^3}$$

(36)

$$\times \frac{\left[1 - \wedge_{OX}^{1/\beta_{OX}}\right]\left[1 - \wedge_{CO}^{(2+3\beta_{CO})/2\beta_{CO}}\right]}{\left[1 - \wedge_{OX}^{(2+\beta_{OX})/2\beta_{OX}}\right]\left[1 - \wedge_{CO}^{(1-2\beta_{CO})/\beta_{CO}}\right]}$$

Since $E(T_R) \approx T_R$ for $T_R \gtrsim 300^\circ K$ this ratio falls off roughly as T^{-2} at high temperatures. The ratio is plotted as a function of T_R in Fig. 1. Table 1 gives the values of the total flux radiated by O and CO from unit optical depth in each constituent for various values of temperature and scale height gradient in the radiation zone. The figures may serve as a useful check on the results of detailed numerical integration of the thermal conduction equation and as a basis for judging the relative effectiveness of these constituents as cooling agents. The temperature difference at unit optical depth in O and CO should be taken into account before quantitative comparisons are made.

6. Nocturnal Temperature Change

Bates compared the total energy content of the Earth's F region (per cm^2 column) with the energy loss rate due to thermal conduction and 62μ O radiation. The character-

Table 1

Total flux radiated from a planetary thermosphere by O and CO. T refers to the temperature at unit optical depth in each constituent and β is the corresponding scale height gradient. The flux is in ergs/cm^2 sec.

β =	0		.1		.2		.3		.4	
T	F_O	F_{CO}	F_O	F_{CO}	F_O	F_{CO}	F_O	F_{CO}	F_O	F_{CO}
100	.010	.002	.012	.002	.012	.003	.012	.004	.013	.005
200	.064	.022	.067	.026	.069	.032	.073	.041	.076	.052
300	.15	.089	.15	.11	.16	.13	.17	.17	.17	.21
400	.25	.24	.27	.29	.27	.37	.28	.45	.28	.55
500	.37	.53	.39	.65	.40	.49	.42	.96	.42	1.2
600	.51	1.0	.52	1.2	.55	1.5	.57	1.8	.59	2.2
700	.66	1.7	.69	2.1	.71	2.5	.73	3.0	.74	3.6
800	.83	2.8	.86	3.3	.88	4.0	.91	4.7	.93	5.5
900	.99	4.2	1.0	5.0	1.1	5.9	1.1	6.9	1.1	8.1
1000	1.2	6.0	1.3	7.1	1.3	8.4	1.3	9.8	1.3	11.

istic time which he obtained as the quotient of these quantities was of the order of several days, and he therefore concluded that nocturnal cooling would be slight. The time-dependent study by Harris and Priester (1962) gives a daily amplitude of exospheric temperature variation of roughly $\pm 200^{\circ}$K about a mean of 1500°K. The amplitude is thus relatively small (± 15-20%).

The situation is quite different if substantial CO is present. We will define the cooling time for CO as the time required for radiation from the rotational states to halve a given initial temperature. If we consider CO cooling alone, the temperature change is described by

$$\rho c_p \frac{dT}{dt} = -k_r \, n_{CO}(z) \, T^2 \tag{37}$$

where $k_r = 2.58 \times 10^{-23}$ erg/$^{\circ}$K^2 sec is the coefficient of the term for the power radiated by CO (see equation (4)). The solution of (37) is

$$T(t) = \frac{T_0}{1 + t/\theta} \tag{38}$$

where T_0 is the initial temperature and

$$\theta = \frac{c_p \rho}{k_r n_{CO} T_0} \tag{39}$$

is the cooling time for CO. If we take the density ρ in (39) to be the sum of the O and CO densities, θ may be expressed as

$$\theta = \frac{c_p m_{CO}}{k_r T_0} \left[1 + \frac{\sigma_D(CO)}{\sigma_D(O)} \left[\frac{m_{OX}}{m_{CO}} \right]^2 \frac{\tau_{OX}}{\tau_{CO}} \right] \tag{40}$$

where m_{CO} is the mass of a CO molecule, m_{OX} the mass of atomic oxygen, $\sigma_D(O)$ and $\sigma_D(CO)$ are the Doppler absorption cross sections given in (18) and (23), and τ_{OX} and τ_{CO} are the isothermal optical depths in O and CO. The temperature dependence not taken into explicit account in passing from (37) to (38), as well as the altitude dependence of θ, appears in the right hand term in the brackets of (40). The Doppler absorption cross sections are temperature-dependent, but the ratio $\sigma_D(CO)/\sigma_D(O)$ does not depend strongly on temperature and is equal to about 5 over a wide temperature range. The first two factors in the right hand term in brackets of (40) are

thus of order unity. The ratio $_{OX}/_{CO}$ is certainly less than one, but since the density, ρ, is likely to be slightly underestimated in (40) we will take the right hand term as equal to 1. The cooling time is thus

$$\theta \approx 2 \; \frac{c_p m_{CO}}{k_r T_0} \tag{41}$$

The approximation made in setting $_{OX}/_{CO} \sim 1$ is thus roughly equivalent to the assumption that the carbon monoxide density (gm/cm^3) in the radiation zone is half the total density. Equation (41) thus contains the implicit assumption that CO_2 is a major atmospheric constituent at the altitude at which it dissociates.

The temperature change as a function of time, evaluated from (38), over a 12-hour period is shown in Fig. 2 for various initial temperatures. The specific heat has been taken as $c_p = 0.2 \; cal/^{O}K$ gm. The cooling time given by (41) is about 7 hours at $1000^{O}K$.

The amplitude of the temperature decrease given in Fig. 2 should be representative of that to be expected in the Martian thermosphere since the rotational period of the planet is about 24 hours. Thus, if the peak

daytime temperature is $\lesssim 1000^\circ$K the temperature of the

nighttime Martian exosphere must fall to $\lesssim 300^\circ$K unless

there is a nocturnal heat source. The rotational period

of Venus is relatively long, being about 250 days retro-

grade (Goldstein and Carpenter, 1963). The nocturnal

temperature in the Venusian thermosphere could thus be

quite low since equilibrium may depend either on energy

transport from the day side, on infrared heating from

the planetary spectrum, or on other low altitude heat

sources. Thermal conduction from the day side could

not maintain a very high temperature on the night side

of the planet. Even with a day-night temperature dif-

ference of 2000°K, the mean horizontal temperature gradient

would be $\approx .05^\circ$K/km, which would transport $\sim .008$ erg/cm^{2}sec.

From Table 1 we see that this flux could be substantially

accommodated by O and CO at temperatures $\approx 100^\circ$K. A

quantitative estimate of the temperature maintained by

infrared heating would require a solution of the radiative

transfer equation, but it would be less than the plane-

tary effective temperature of $\sim 230^\circ$K.

7. Summary and Conclusions

The effectiveness of atomic oxygen and carbon monoxide

as radiative cooling agents in a planetary thermosphere has been investigated. Analytic expressions for the total flux radiated by each constituent were developed and it was shown that for temperatures $\lesssim 300^{\circ}K$ in the radiation zone the total energy loss in the 62_{μ} oxygen line may equal or exceed that in the CO rotational lines. The figures given in Table 1 for the total flux radiated by each constituent depend on the efficacy of a Bates' type of cooling approximation for their validity, but the conclusions drawn in this paper as to the relative cooling effectiveness of O and CO are not so dependent.

It has been shown that substantial overnight cooling will occur in planetary exospheres containing CO. The amplitude of the day-night temperature variation in the Martian exosphere is probably about 50% in contrast to a 15-20% diurnal variation in the Earth's exosphere. The nocturnal temperature minimum in the Martian exosphere must be $\lesssim 300^{\circ}K$ if the peak daytime temperature is $\lesssim 1000^{\circ}K$, as it must be for the retention of atomic oxygen by the planet (Chamberlain, 1962). The Venusian exosphere must also be rapidly cooled by CO. Due to the length of the night on Venus the equilibrium exospheric temperature

must be maintained either by horizontal energy transport
or by heating from lower altitudes. Horizontal conduc-
tion from the day side could not maintain a nighttime
temperature in excess of $\sim 100^{O}$K.

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LEGENDS

Fig. 1. Ratio of O to CO radiated flux. The curves are labeled according to the values of the scale height gradient β_{OX} for O.

Fig. 2. Decrease in temperature with time due to infrared radiation from CO.