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The purpose of this note is to show that a simple scaling law, based on an approximate solution of the heat balance equation, can be used to determine the variation of exospheric temperature T_∞ over a solar cycle. T_∞ is defined as the temperature of the isothermal region (on account of heat conduction) extending into the exosphere. Thus, T_∞ also controls the escape of gases from planetary atmospheres.

It is assumed that in the thermosphere, the effective heat input due to EUV radiation, Q_{uv}, is balanced by the divergence of a conductive heat flux, E (neglecting IR radiation from atmospheric constituents) according to

$$\text{div } E = Q_{uv} \tag{1}$$

where $E = -K_n (T)\, dT/dz$, with $K_n (T)$ the thermal conductivity and the dT/dz the temperature gradient with altitude and $Q_{uv} = n_j \sigma_a \epsilon_j I_\infty e^{-\tau}$ with n_j the number density of the absorbing constituent, σ_a its average absorption cross section, ϵ_j the heating efficiency of solar EUV radiation of intensity I_∞ outside the atmosphere (i.e., in the exosphere) and $\tau = \int_0^z n_j \sigma_a \, dz$ the optical depth.

The integrated form of (1) is given by

$$\int_{z_0}^{z_\infty} \epsilon_j I_\infty (1 - e^{-\tau})\, dz = \int_{T_0}^{T_\infty} K_n (T)\, dT \tag{2}$$

where T_∞ is the exospheric temperature, T_0 is the temperature at the mesopause and z_∞ and z_0 are the corresponding altitudes.

In the aeronomic literature it is generally assumed that $K_{nj} = A_j \; T^{1/2}$ based on a rigid sphere approximation.[1] However, as pointed out recently,[2] such a temperature dependence may not always be applicable. Experimental data[3] and quantum-mechanical calculations[4] show that for atmospheric gases $K_{nj} = K_0 \, T^{\nu j}$, where $\nu_j > 0.5$, so that the temperature dependence in the heat conduction equation will not be identical for all planetary atmospheres as the result of their different composition. ($K_O = 67 \; T^{0.71}$, $K_{CO_2} = 1.5 \times T^{1.23}$, $K_{He} = 21 \; T^{0.75}$ and $K_H = 16.4 \times T^{0.73}$)[3,4]

Integration of (2) following some simplifications leads to

$$\frac{\epsilon_j \; I_\infty}{n\,(z_\infty)\;\sigma_a} \simeq K_0 \; (T_\infty^{\nu+1} - T_0^{\nu+1}) \tag{3}$$

if we assume that $\tau \to 0$ at z_∞, i.e., in the exosphere, and $\tau \to \infty$ at z_0, i.e., at the base of the thermosphere, and allowing for $(n\,(z_\infty)\;\sigma_a)^{-1} \gg z_\infty - z_0$ (since $\sigma_a \simeq 10^{-17}$ cm^2 and exospheric densities are of the order 10^8 cm^{-3}). For $n\,(z_\infty)$ we substitute the density at the exobase $n_b \simeq (\sigma_c\, H)^{-1}$ which derives from the exospheric condition that the mean free path is of the order of the local scale height $H = k\,T_\infty\,/mg$, where k is the Boltzmann constant, m is the mean mass and g is the acceleration of gravity at the exobase and σ_c is the gas kinetic collision cross section.

Thus, we can write (3), neglecting T_0 compared to T_∞ (which seems permissible, at least for the terrestrial planets) as

$$T_\infty^\nu \propto \frac{\epsilon_j I_\infty k \sigma_c}{K_0 mg \sigma_a} \tag{4a}$$

and thus

$$T_\infty \propto I_\infty^{1/\nu} \tag{4b}$$

From satellite drag observations over a solar cycle[5] it is known that the terrestrial exospheric (daytime) temperature ranges from ~800°K at solar minimum to ~2000°K at solar maximum leading to a ratio T_∞ (SMax)/T_∞ (SMin) ≃ 2.5. Although an empirical relation exists between solar 10.7 cm radio flux, $S_{10.7}$ (which is an indicator of solar activity) and exospheric temperature,[5] the exact relationship between $S_{10.7}$ and the EUV intensity I_∞ has yet to be established. Since for the terrestrial thermosphere, $T_\infty \propto I_\infty^{1/0.71}$, we infer from a temperature ratio of 2.5, that the EUV intensity has changed by a factor ~1.9 over the solar cycle. This seems to be consistent with observations[6] and modelling of the terrestrial ionosphere.[7]

For a CO_2 atmosphere (Mars, Venus) where $T_\infty \propto I_\infty^{1/1.23}$ holds, we obtain a temperature ratio over the solar cycle of ~1.7. For Mars, Mariner 4 observations[8] near solar minimum showed an exospheric temperature $T_\infty \approx 300$°K, while Mariner 6 and 7 measurements[9] near solar maximum showed $T_\infty \approx 500$°K. Our estimated ratio of T_∞ over a solar cycle, thus agrees well with the observations. For Venus, Mariner 5 measured $T_\infty \approx 650$°K near the middle of the solar cycle.[10] Thus, according to our estimate, the exospheric temperature of Venus at solar minimum should be $T_\infty \approx 470$°K and that at solar maximum $T_\infty \approx 800$°K.

Recently it was suggested[11] that the ratio of thermal energy 3/2 kT, to gravitational energy $m_H gr$, of hydrogen is about 1/2 for the solar corona as well as for the earth's exosphere (r is the planetocentric distance). This leads to the condition that the thermal velocity of hydrogen $v_{th} = (3\ kT/m_H)^{1/2}$ is about equal to its circular orbital velocity $v_0 = \sqrt{gr}$. (Note that the escape velocity $v_\infty = \sqrt{2}\ v_0$). From this relationship Matora[11] estimated the "limiting" exospheric temperature of a planet to be given by $T_\infty \approx m_H gr/3\ k$. Accordingly, he obtained the estimates of $T_\infty \approx 400°K$ for Mercury, 800°K for Venus, 2000° for Earth, 300°K for Mars and 25,000°K for Jupiter as exospheric temperature for a gravitationally stable atmosphere. This limit is similar to the condition of Öpik[12] according to which atmospheres with an escape parameter $B \equiv mgr/kT_\infty < 1.5$ are unstable. This condition corresponds to $v_{th}/v_0 = \sqrt{2}$ or $v_{th}/v_\infty = 1$. (It should be noted, however, that with significant escape, the "effective" temperature well above the exobase, will be less than T_∞ due to the loss of high velocity particles).[13]

Thus, Earth and Venus seem to have exospheres which are stable even at solar maximum although they are subject to escape (B < 15), while the exosphere of Mars is stable only near solar minimum, and escape should be excessive near solar maximum.

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REFERENCES

1. Nicolet, M., Ch. 2, in Physics of the Upper Atmosphere (edit. by J. A. Ratcliffe), (Academic Press, 1960).

2. Shimizu, M., Inst. Space and Aeronaut. Sci., Univ. of Tokyo, Rept. No. 455, (1970).

3. Tsederberg, N. V., Thermal Conductivities of Gases and Liquids, (MIT Press, 1965).

4. Dalgarno, A., and Smith, F. J., Planet. Space Sci. 9, 1 (1962); Proc. Roy. Soc. A267, 417 (1962).

5. Jacchia, L. G., Annls. IQSY, Vol. 5, Paper 17, (1969).

6. Hall, L. A., Schweizer, W., and Hinteregger, H. E., J. Geophys. Res. 70, 2241 (1965). Hall, L. A., Higgins, J. E., Chagnon, C. W. and Hinteregger, H. E., J. Geophys. Res. 74, 4181 (1969).

7. Herman, J. R., and Chandra, S., Planet. Space Sci., 17, 815 (1969).

8. Fjeldbo, G., and Eshelman, V. R., Planet. Space Sci., 16, 1035 (1968).

9. Kliore, A. J., Fjeldbo, G., and Seidel, B. L., Barth, C. A., 13th COSPAR Mtg., Leningrad USSR, 1970.

10. Barth. C. A., J. Atmos. Sci., 25, 564, 1968.

11. Matora, I. M., SOVIET PHYSICS -- DOKLADY (Astronomy), Vol. 15, No. 2, 83 (1970).

12. Öpik, E. J., Geophys. J. (RAS), 490 (1963).

13. Chamberlain, J. W., Planet. Space Sci., 11, 901, (1963).