Abstract. The temperature distributions in cometary atmospheres at various heliocentric distances for comets of Bennett and Encke types have been calculated by taking into account heating due to the absorption of solar ultraviolet radiation, cooling by H₂O far infrared emission, and various dynamical processes (expansion, advection, and thermal conduction). The agreement of the results with the observations is in general satisfactory. The conversion of CH₄ and NH₃ to CO and N₂ through thermochemical reaction with H₂O is concluded to be impossible, since the temperature is too low at a heliocentric distance 1.5 AU where CO⁺ ions begin to be observable.

1. Introduction

The kinetic temperature of a cometary atmosphere (inner coma) is a good measure of the energy balance between the solar ultraviolet radiation and a comet. It is also an important factor in the determination of the volatile composition of cometary nuclei, as has been discussed in detail in previous papers (Shimizu, 1975a, 1975b): If the temperature at an atmospheric level of a comet is higher than, say, 1500 K, the nuclei may be composed of dirty ice of the first kind (H₂O, CH₄, and NH₃), since the chemical reactions among these gases in the atmosphere form CO and N₂ whose ions have been observed in type I tails. If the temperature is low throughout the cometary atmosphere, the nuclei should contain H₂O, CO, and N₂ (dirty ice of the second kind), probably in the form of hydrate clathrates, as suggested from the composition of interstellar molecules.

Direct observation of the kinetic temperature of cometary atmospheres is not easy. Astronomers have usually determined the rotational temperature of various molecules by analysing the spectrum of the resonantly scattered solar visible radiation. However, the rotational temperature does not well represent the kinetic temperature, since the radiative processes seriously modify the thermal population among rotational levels. In reality, the observed rotational temperatures span a wide range, from 30 K for H₂O⁺ to 3000 K for C₂. A more careful study to pick up collisional effects in a high resolution spectrum of CN resulted in a kinetic temperature 300 K at a heliocentric distance 1 AU (Malaise, 1970). OAO II measured the Doppler width of a Lyman alpha emission line of Comet Tago-Sato-Kosaka in the vicinity of its perigee and an ‘apparent’ temperature 1600 K has been obtained, by assuming the profile to be Gaussian (Code and Savage, 1972). Another theoretical analysis of the observed
Lyman alpha brightness distribution in the vicinity of the nucleus of Comet Bennett at 0.81 AU led to the suggestion of a very high temperature of 3000 K (Mendis et al., 1971). Obviously this temperature is in contradiction not only with Malaise's conclusion but with other previous observations for the temperatures in the outer regions of cometary comas.

Since the observed temperatures are so scattered, a detailed theoretical study of the thermal structure in cometary atmospheres appears to be necessary. The author has already considered this point in a qualitative manner, by taking into account heating due to absorption of the solar ultraviolet radiation and cooling through the far infrared emission of H2O in a LTE state. In addition to these processes, various dynamical effects (expansion, advection, and thermal conduction) and the effects of non-LTE type cooling will be taken into account in this paper and quantitative numerical computations will be carried out to find the temperature distributions in two kinds of cometary atmospheres (Bennett and Encke) at various heliocentric distances.

2. Models of Cometary Atmospheres and Thermodynamical Equation

The main constituent of cometary nuclei appears to be H2O. Recent observations of H2O, H2O\(^+\), OH, H, and O at various wavelengths of radiation evidently support this conclusion. Bright comets such as Bennett and Kohoutek have a molecular mass loss rate of \(\sim 10^{30} \text{s}^{-1}\) at 1 AU. The atmospheric densities at the cometary surfaces are \(\sim 10^{12} \text{ cm}^{-3}\) assuming a radius of 10 km. The density decreases outward in proportion to the inverse square of \(r\), the distance from the center of the comet. The molecular mass loss rates of all comets have a dependence on the heliocentric distance \(R\) in a form of \(R^{-2}\), according to the observation of H atom Lyman-alpha emission (Keller, 1974). On the other hand, a short period comet such as Encke would have a smaller mass loss rate by two orders of magnitude than that of a bright comet.

The thermodynamical equation which governs the temperature distribution in cometary atmospheres may be written as

\[
q \rho v \nabla T + \rho \text{div} \nabla T + \text{div} \Phi_{\text{cond}} = Q - L, \tag{1}
\]

where \(q\) is the atmospheric mass density; \(c_v\), the specific heat at constant volume; \(v\), the gas velocity; \(T\), the atmospheric temperature; \(\rho = NkT\) the atmospheric pressure; \(N\), the atmospheric number density; and \(k\), the Boltzmann constant. Furthermore,

\[
\Phi_{\text{cond}} = -K(T) \nabla T,
\]

where \(K\) is the thermal conduction coefficient of water and can be expressed as

\[
10^4K(T) = 2.3012T + 0.011 \times 637T^2 - 0.042 \times 492T^3 \quad (\text{erg s}^{-1} \text{ cm}^{-1} \text{ K}^{-1}). \tag{2}
\]

The first, second, and third terms on the left-hand side of the Equation (1) correspond