DEUTERIUM DISTRIBUTIONS IN THE EARTH'S UPPER ATMOSPHERE

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The physical conditions leading to a deuterium enhancement in the earth's upper atmosphere are discussed as a function of the thermopause temperature and of the eddy diffusion coefficient. It appears that changes in the eddy diffusion can induce large variations in the deuterium concentration for temperatures less than 1500 °K. Under those conditions, the inefficiency of thermal escape should be compensated by the polar wind process. As the deuterium total content is relatively small compared with that of atomic hydrogen, the best observational conditions occur for thermopause temperature around 1250 °K.

Deuterium ions were detected [1, 2] in the earth's upper atmosphere by a magnetic mass spectrometer flown in 1965 on the Explorer 31 satellite. The ratio of the concentrations $n(D^+)/n(H^+)$ was estimated to be of the order of 1.1×10^{-3} below 1000 km, but it decreased by a factor of 10 above 2000 km [2]. High-resolution profiles of the solar H Lyman α line [3, 4] seem to indicate an atmospheric absorption effect due to deuterium at 1215.346 Å.

The presence of deuterium above 100 km probably results from a complex set of photochemical reactions in the chemosphere and an approach to the problem should be made in a way similar to Nicolet's method for atomic hydrogen [5], although unknown isotopic effects could be important in determining the reaction rates. In the present analysis, a ratio $n(D)/n(H) = 1.6 \times 10^{-4}$ is adopted at 100 km altitude, without trying to explain it by photochemical and transport processes in the stratosphere and mesosphere. Such a value corresponds to the deuterium content of standard mean ocean water [6, 7]. With an atomic hydrogen concentration $n(H) = 3 \times 10^7$ cm^{-3} at 100 km, which is necessary to explain the OGO 4 Lyman-α observations [8], the lower boundary condition adopted for the concentration of deuterium is 4.8×10^3 cm^{-3}. This value could be decreased by a factor of 2, since a recent analysis [9] of several Lyman-α observations shows that the hydrogen concentration could be between 1.25 and 2×10^7 cm^{-3}.

In a previous theoretical analysis, Kockarts and Nicolet [10] showed that the ratio $n(D)/n(H)$ can increase by a factor 20 between 100 and 500 km for a large range of thermopause temperatures when molecular diffusion is introduced in the thermosphere. In the present work, a general diffusion equation, including molecular and eddy diffusion transport, is used in the way described by Kockarts [11]. Similar equations were applied by Donahue [12] and by

McElroy and Hunten [13] in different studies on deuterium in the atmosphere of Venus.

Above 100 km in the earth's thermosphere, the vertical distribution of deuterium depends mainly on the temperature, on the escape flux and on the value adopted for the eddy diffusion coefficient. The relative importance of these factors is determined by the atmospheric structure. In Fig. 1 the variation of the deuterium concentration is shown as a function of the thermopause temperature when the eddy diffusion coefficient K is 10^7 cm^2 s^{-1}. For atomic hydrogen it has been shown [10] that the diffusion flow leads to an
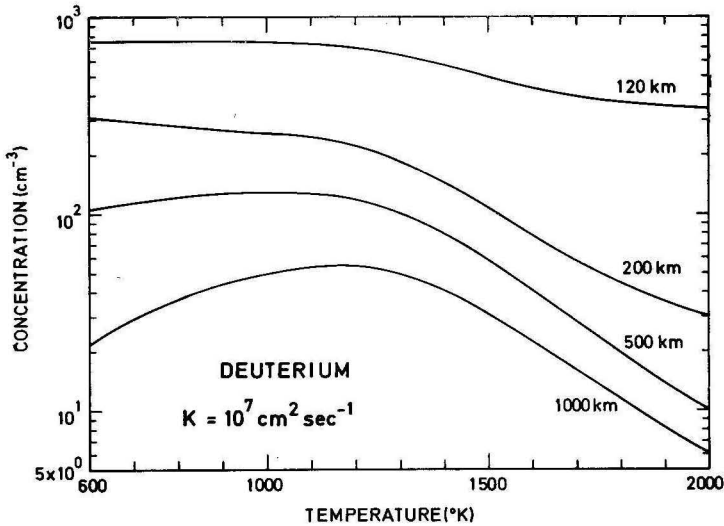

Fig. 1. Deuterium concentration at different heights as a function of the thermopause temperature with eddy diffusion coefficient $K = 10^7$ cm^2 s^{-1}.

increase of the concentration with a decrease of the thermopause temperature. For deuterium, however, there are concentration peaks at various heights for temperatures between 600 °K and 1500 °K. Above 1500 °K, $n(D)$ always decreases with increasing temperature. The deuterium behaviour is similar to that of atomic hydrogen for high thermopause temperatures. Nevertheless, if $T < 1500$ °K, the vertical distribution of deuterium has a tendency to be similar to that of helium, since the concentration at 500 km hardly varies with changes in thermopause temperature. Moreover, the greatest variation of $n(D)$ at 1000 km does not reach a factor of 10 whereas, under steady state conditions, the atomic hydrogen concentration increases by a factor of 200 between 2000 °K and 600 °K. Furthermore, the deuterium escape flux cannot be constant over a wide temperature range, since the effusion velocity decreases by a factor 2×10^6 from $T = 2000$ °K to $T = 600$ °K. For $K = 10^7$ cm^2 s^{-1}, the deuterium escape flux decreases actually from 8×10^3 cm^{-2} s^{-1} ($T = 2000$ °K) to 1.4 cm^{-2} s^{-1} ($T = 750$ °K). If the escape flux corresponds to the possible flow of 10^4 cm^{-2} s^{-1} at 100 km, it is necessary to consider a charge exchange

process with atomic oxygen ions in order to obtain an equivalent ionic escape flux through the polar wind.

The vertical distribution of a minor constituent in the thermosphere depends strongly on the adopted values for the eddy diffusion coefficient, when the
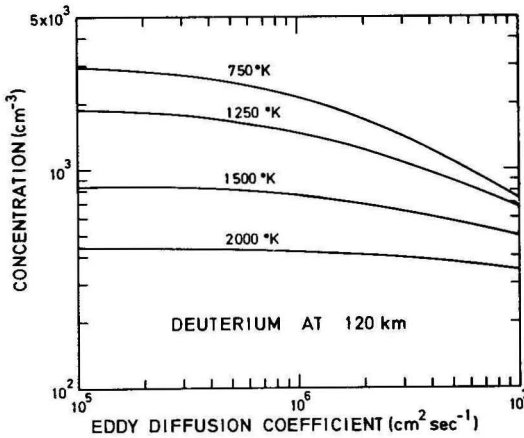

Fig. 2. Variation of the deuterium concentration with eddy diffusion coefficient for thermopause temperatures between 750 °K and 2000 °K.
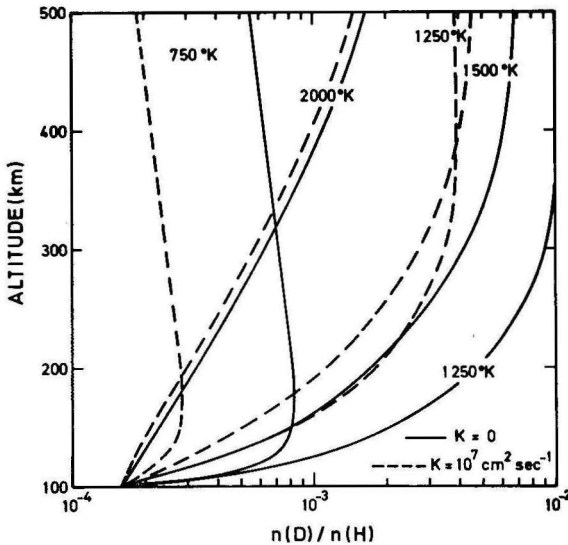

Fig. 3. Height dependence of the ratio $n(D)/n(H)$ for different thermopause temperatures. The adopted eddy diffusion coefficients are respectively $K = 0$ and 10^7 cm² s⁻¹.

escape of neutral particles is negligible compared with the maximum diffusion flow around 100 km [11]. Fig. 2 shows the deuterium concentration at 120 km as a function of K for different thermopause temperatures. The most important variations appear for temperatures less than 1500 °K. Actually, for $T = 1500$ °K

the escape flux is respectively 9.8×10^3 cm^{-2} s^{-1} and 5.2×10^3 cm^{-2} s^{-1} with $K = 0$ and $K = 10^7$ cm^2 s^{-1}, whereas the maximum diffusion flow at 100 km is 1.3×10^4 cm^2 s^{-1}. Below 1500 °K, the vertical deuterium distribution depends both on the temperature and on the adopted value for K. For example, at 1000 km, $n(D) \simeq 3 \times 10^1$ cm^{-3}, when $T = 1500$ °K or 750 °K and with $K = 10^7$ cm^2 s^{-1}; however at the same height, $n(D) \simeq 1.6 \times 10^2$ cm^{-3}, when $T = 1250$ °K or 750 °K and with $K = 0$.

The effect of the escape flux for $T > 1500$ °K and the effect of eddy diffusion for $T < 1500$ °K together influence the vertical distribution of the ratio $n(D)/n(H)$ given in Fig. 3. This ratio actually goes through a maximum which occurs at an altitude depending on the thermopause temperature. In Fig. 3 it is shown that the maximum enhancement of the ratio $n(D)/n(H)$ occurs around 400 km for $T = 1250$ °K; it corresponds to almost 60 times the adopted natural abundance of 1.6×10^{-4} when $K = 0$ above 100 km. This enhancement is about a factor of 3 less than that deduced by Bruner and Wilson [3] at 160 km altitude. Moreover, the theoretical ratios given in Fig. 3 are of the same order of magnitude as the ratios $n(D^+)/n(H^+)$ measured by Hoffman et al. [2]. It should be noted that $n(D)/n(H)$ begins to decrease above a certain height and can even reach values less than the assumed abundance at 100 km. This means that the diffusion transport can lead to an increase of the ratio $n(D)/n(H)$ only over a certain height range.

Finally, it should be pointed out that optical observations of deuterium in the earth's atmosphere are extremely difficult, since the total content is such that the optical depth at the centre of the deuterium Lyman-α line is very small. For example, at 100 km, the vertical content of deuterium ranges from 6.7×10^{10} cm^{-2} to 5.6×10^9 cm^{-2}, depending both on the adopted eddy diffusion coefficient and on the thermopause temperatures. In any case observations above 200 km should be performed when the deuterium enhancement reaches its maximum, i.e. for a thermopause temperature of the order of 1250 °K.

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