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Deuterium distributions in the Earth's upper atmosphere

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FOREWORD

This paper has been presented at the symposium on "Dynamics of the thermosphere and ionosphere above 120 km" held at Seattle (June 24-26, 1971) during the XIV Plenary meeting of COSPAR. It will be published in the proceedings of this symposium.

AVANT-PROPOS

Ce travail a été présenté au symposium "Dynamics of the thermosphere and ionosphere above 120 km" qui a eu lieu du 24 au 26 juin 1971, lors de la 14e assemblée plénière du COSPAR à Seattle. Ce texte sera publié dans les comptes-rendus du symposium.

VOORWOORD

Dit werk is voorgedragen geworden gedurende het Symposium over de "Dynamics of the thermosphere and ionosphere above 120 km" dat plaats vond van 24 tot 26 juni 1971, tijdens de 14e algemene vergadering van COSPAR te Seattle. De tekst van de mededeling zal verschijnen in het verslag van dit Symposium.

VORWORT

Dieser Text wurde während der 14. COSPAR Versammlung in Seattle zum Symposium "Dynamics of the thermosphere and ionosphere above 120 km" vorgestellt (24.-26. Juni 1971). Er wird mit den anderen Darlegungen in einem Buch herausgegeben werden.

DEUTERIUM DISTRIBUTIONS IN THE EARTH'S UPPER ATMOSPHERE

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Abstract

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 to that of atomic hydrogen, the best observational conditions occur for thermopause temperature around 1250°K.

Résumé

Les conditions physiques susceptibles de conduire à un accroissement du deutérium dans l'atmosphère supérieure de la terre sont analysées en fonction de la température de la thermopause et des valeurs adoptées pour le coefficient de diffusion turbulente. Lorsque la température est inférieure à 1500°K, une modification du coefficient de diffusion turbulente peut induire de grandes variations de la concentration en deutérium. Dans ce cas, le faible flux d'échappement thermique doit être compensé par un échappement ionique dans le cadre du vent polaire. Comme le contenu total en deutérium est relativement faible par rapport à l'hydrogène atomique, les meilleures conditions d'observation se présentent lorsque la température de la thermopause est de l'ordre de 1250°K.

Samenvatting

De fysische omstandigheden, die kunnen leiden tot een toename van deuterium in de opperatmosfeer van de aarde, worden bestudeerd in functie van de temperatuur van de thermopauze en van de aangenomen waarden voor de diffusiecoëfficiënt in de aanwezigheid van wervelingen. Wanneer de temperatuur onder de 1500°K blijft, heeft een wijziging van de diffusiecoëfficiënt een grote weerslag op de concentratie van het deuterium. In dit geval moet de geringe thermische ontsnappingsflux gecompenseerd worden door een ionische ontsnapping volgens het model van de poolwind. Aangezien de totale hoeveelheid deuterium t.o.v. de atomaire waterstof betrekkelijk gering is zijn de beste waarnemingsvoorwaarden deze waarbij de temperatuur van de thermopauze van de orde van 1250°K is.

Zusammenfassung

Die physikalische Bedingungen, die zu einem Zusatz von Deuterium in der höheren Atmosphäre der Erde führen können, werden in Verbindung mit der Thermopausetemperatur und mit den Eddydiffusionskoeffizienten zu grossen Variationen der Deuteriumdichte führen. In diesem Fall, soll der thermische Ausströmungsfluss durch einen ionischen Fluss (polar wind) ersetztwerden. Da der Deuteriuminhalt ziemlich klein ist im Vergleiche mit Wasserstoff, werden die besten Beobachtungsbedingungen für eine Thermopausetemperatur von 1250°K stattfinden.

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 OGO4 Lyman-α observations [8], the adopted lower boundary condition 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] is 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 adopted value for the eddy diffusion coefficient. The relative importance of these factors is determined by the atmospheric structure. In Fig. 1. the 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 sec^{-1}. For atomic hydrogen, it has been shown [10] that the diffusion flow leads to an 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 behavior 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 sec^{-1}, the deuterium escape flux decreases actually from 8×10^3 cm^{-2} sec^{-1} (T = 2000°K) to 1.4 cm^{-2} sec^{-1} (T = 750°K). If the escape flux corresponds to the possible flow of 10^4 cm^{-2} sec^{-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 escape of neutral particles is negligible compared to 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

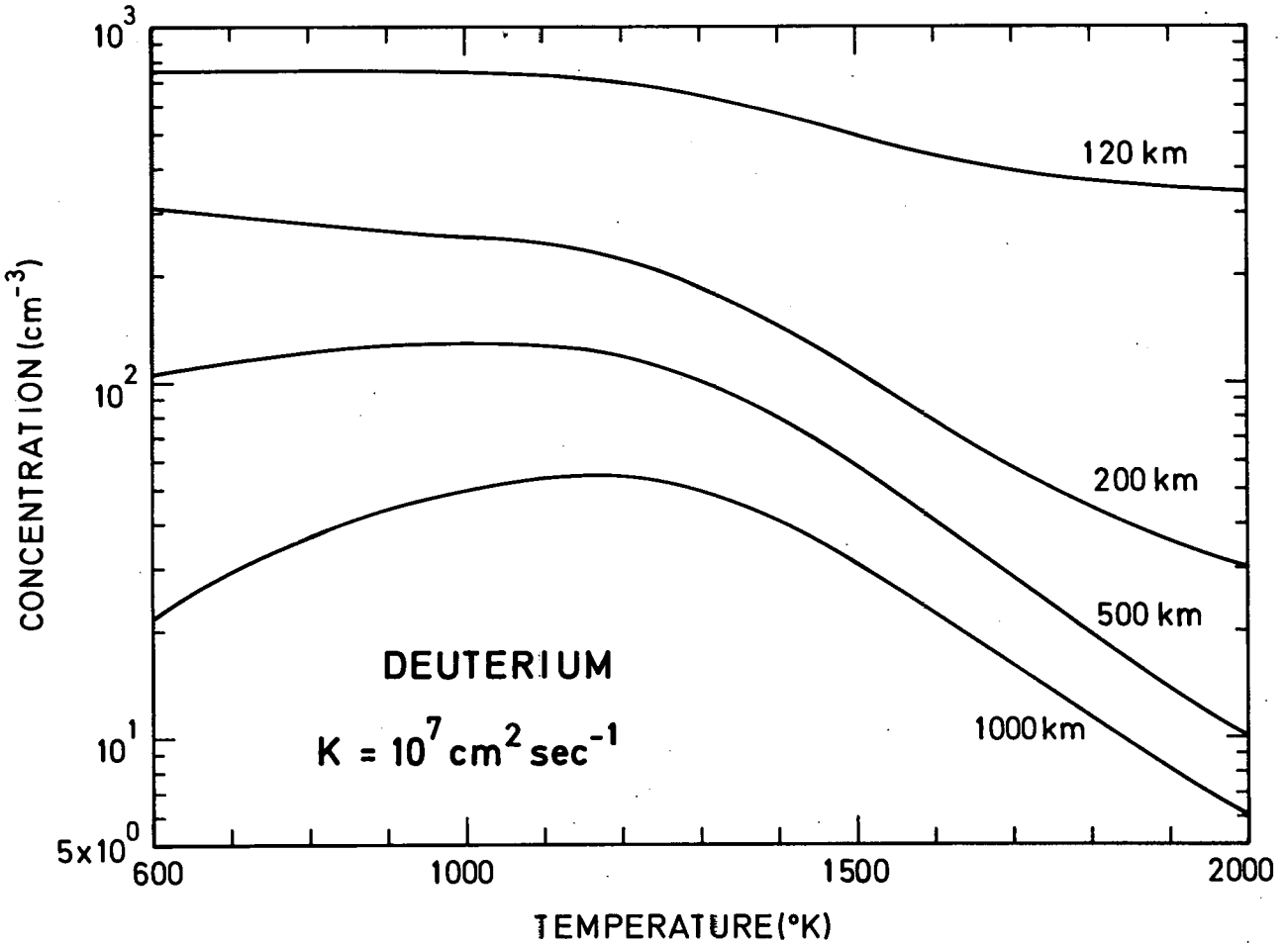

Fig. 1.- Deuterium concentration at different heights as a function of the thermopause temperature with eddy diffusion coefficient $K = 10^7$ cm^2 sec^{-1}.

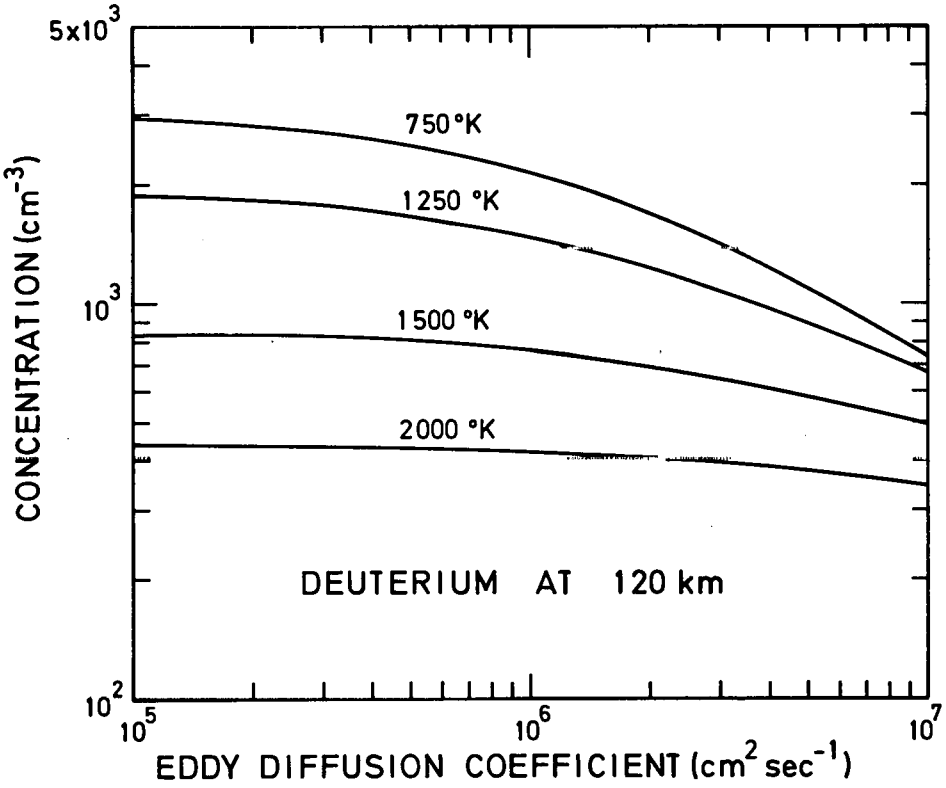

Fig. 2.- Variation of the deuterium concentration with eddy diffusion coefficient for thermopause temperatures between 750°K and 2000°K.

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

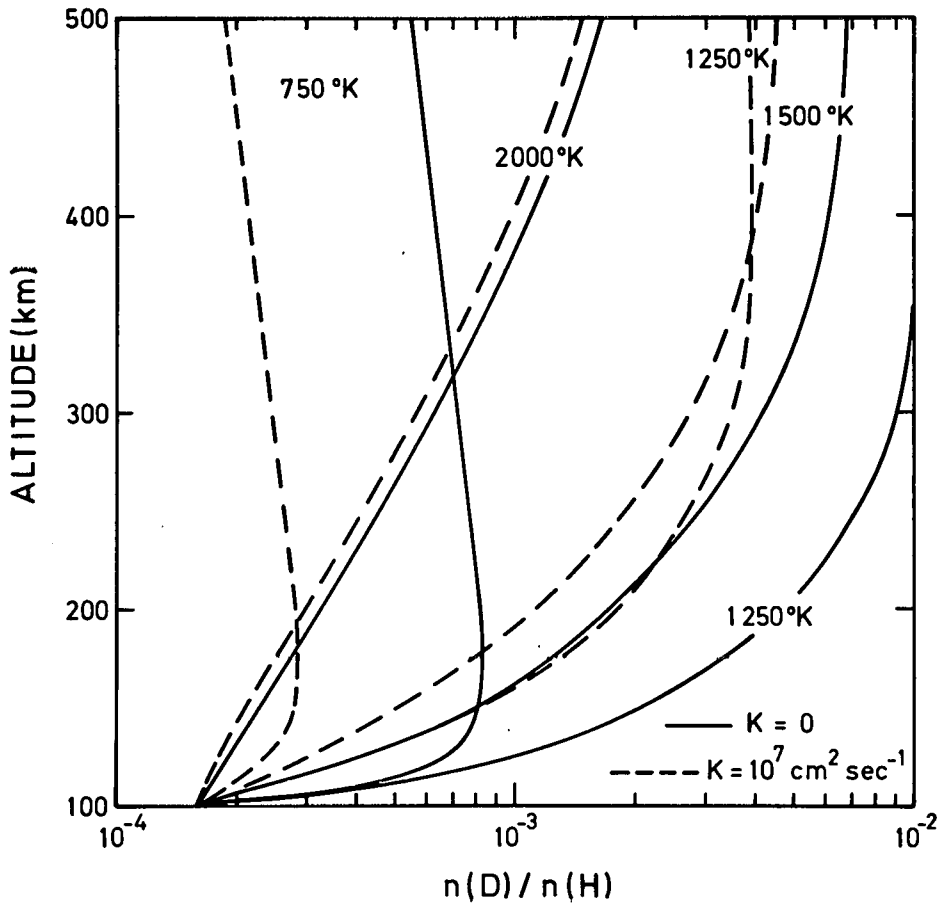

Fig. 3.- Height dependence of the ratio n(D)/n(H) for different thermopause temperatures. The adopted eddy diffusion coefficients are respectively K = 0 and 10^7 cm^2 sec^{-1}.

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