ULTRAVIOLET STELLAR OCCULTATION MEASUREMENT OF THE H_2 AND O_2 DENSITIES NEAR 100 KM IN THE EARTH'S ATMOSPHERE

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Abstract. The density of molecular hydrogen in the earth's atmosphere has been measured between 95 km and 108 km. The technique involved use of the high resolution ultraviolet spectrometer of the Orbiting Astronomical Observatory Copernicus to observe radiation from the γ^2 Velorum near the R(0) line of the (0,0) Lyman absorption band at 1108Å as the star was occulted by the earth's atmosphere. The result shows H_2 densities varying from $1.05^{+0.15}_{-0.14} \times 10^8 cm^{-3}$ at 95 km to $1.1^{+0.05}_{-0.08} \times 10^7 cm^{-3}$ at 108 km. These densities agree quite well with recent theoretical predictions. The measured O_2 density profile generally agrees with the models except for a wave-like structure between 104 km and 114 km.

INTRODUCTION

This letter will report the results of the first successful attempt to measure the density of H_2 near 100 km in the earth's atmosphere. In addition, the measurement of the O_2 density between 95 km and 123 km will be reported. The technique employed involved observation of the occultation of a star, γ Vel, by the earth's atmosphere at several wavelengths near the H_2 absorption line at 1108.128Å by the spectrometer on the Orbiting Astronomical Observatory Copernicus. The purpose of the experiment was to test the predictions of a model of the distribution of hydrogen constituents, H, H_2, H_2O, CH_4, OH, and HO_2 in the upper atmosphere related to a theory of hydrogen escape developed by Hunten and Strobel [1974] and by Liu and Donahue [1974a, b, c]. According to a model proposed by the latter authors, H_2 produced dominantly by the reaction R_{23} (the reactions are numbered according to Table 1 of Liu and Donahue, 1974c)

$$H + HO_2 \xrightarrow{k_{23}} H_2 + O_2 \qquad (1)$$

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at about 83 km should be flowing upward near 100 km and should dominate all hydrogen constituents near 100 km except perhaps H. The ratio of H_2 to H is determined principally by the rate constant k_{23} for R_{23}, and by the rate constant k_{17} for R_{17}

$$OH + HO_2 \xrightarrow{k_{17}} H_2O + O_2 \qquad (2)$$

The absolute values of the densities are determined mainly by the mixing ratio of hydrogenic compounds in the stratosphere - more exactly the mixing ratio of the total amount of atomic hydrogen in these compounds.

OBSERVATION TECHNIQUE DATA AND RESULTS OF ANALYSIS

The principle of the experiment is to deduce the density profile from observing the absorption of light flux of a bright star at a given wavelength by the specie of interest in the earth's atmosphere. The absorption spectrum of molecular hydrogen consists of absorption bands longward of 840Å. The Lyman and Werner bands of H_2 are characterized by sharp rotational lines. Molecular oxygen also has absorption bands and a weak underlying continuum which overlaps the spectral region of the H_2 Lyman and Werner bands. The columnar abundance of H_2 in the atmosphere of earth is suspected to be much lower than that of O_2 at any altitude. The technique of mapping the H_2 density, therefore, involves selecting those rotational lines of H_2 at which the O_2 absorption cross section has a minimum. The optical depth in H_2 may be greater than or nearly the same as the optical depth in O_2 at the wavelengths of some of these lines. One such H_2 line which satisfies the optical depth criterion most strongly near 100 km is the Lyman system R(0) line of the (0,0) band at 1108.128Å. For this reason, and because at this wavelength absorption by species other than H_2 and O_2 near 100 km in the atmosphere of earth is insignificant, 1108.128Å line was selected for the observations. At this wavelength, the H_2 oscillator strength is 0.00173 [Morton and Dinerstein, 1976] and the total absorption cross section of O_2 is $5.4 \times 10^{-21} cm^2$ [Watanabe, 1958]. The observations were carried out using the Princeton University ultraviolet spectrometer on board the Orbiting Astronomical Observatory Copernicus. The satellite is in a near circular orbit of altitude 745 km, inclination 35°, and orbital period of 99.7 minutes. For the best available spectral resolution at the wavelength of interest a photomultiplier tube U1 of the Princeton spectrometer having a bandpass of 0.04Å at 1108Å was selected. The spectrometer field of view is 0.3 arc sec x 39 arc sec. The observing date and the target star were selected for the limb grazing rather than the limb crossing geometry in order to optimize the viewing time for the observation of line of sight absorption. A very bright star, γ Vel (HD 68273; type: hot O; V = 1.83), which has continuum flux of approximately 3000 photons $cm^{-2}s^{-1}Å^{-1}$ at 1100Å was tracked over five significant and consecutive Copernicus orbits in which absorption took place clearly outside the South Atlantic Anomaly region. In addition, several unattenuated spectral scans of the target star, γ Vel, centered at 1108Å were made in order to determine the presence of any intrinsic stellar or interstellar spectral features at the H_2 wavelength. Fortunately, no such features at and in the immediate vicinity of 1108.128Å were detected. The absorption experiment was carried out on April 27, 1976 within one hour of the local midnight at the tangent point in order to minimize guidance errors. The minimum tangent altitude increased in the five orbits by approximately 12 km per orbit from 51 km to 97 km due to the node precession of the satellite. The spectrometer was positioned three standard wavelength steps, Δλ, short of 1108.128Å in the first orbit occultation so that the instrument function was clearly outside the wings of the H_2 absorption profile which has a doppler half width of 0.0078Å at 200°K. Δλ is 0.022Å for the spectrometer used. The spectrometer position was moved by Δλ in each orbit so that the H_2 absorption line profile centered at 1108.128Å was entirely within the spectrometer instrument profile in the fourth orbit. We show in Figures 1 and 2 the data of these two orbits in the relevant altitude range. The observed count rates at the end of each 14 sec integration period as a function of universal time are shown by solid circles. The count rates shown have been corrected for the dark count rate of the tube. The chief contribution to the background noise in the U1 tube is cosmic ray charged particle induced and is generally small - on the order of 1 to 2 counts per sec. The unattenuated continuum level of the star above the earth's atmosphere is about 1900 counts sec^{-1}. The variation of the tangent altitude as a function of universal time is shown by the curves labeled Z(t) in Figures 1 and 2. Numerical interpolation between the counting rate data were carried out by using the cubic spline fit, logarithmic fit, and the least squares fit. The results in all cases were nearly identical due to the good quality of the data. Comparison of the counting rates at identical altitudes in the two figures will show a large depletion in orbit 4 below 110 km. For example, the arrows indicating the count rates at 100 km show that at this altitude, the counting rate in orbit 4 was only half that in orbit 1. This reduction is caused presumably

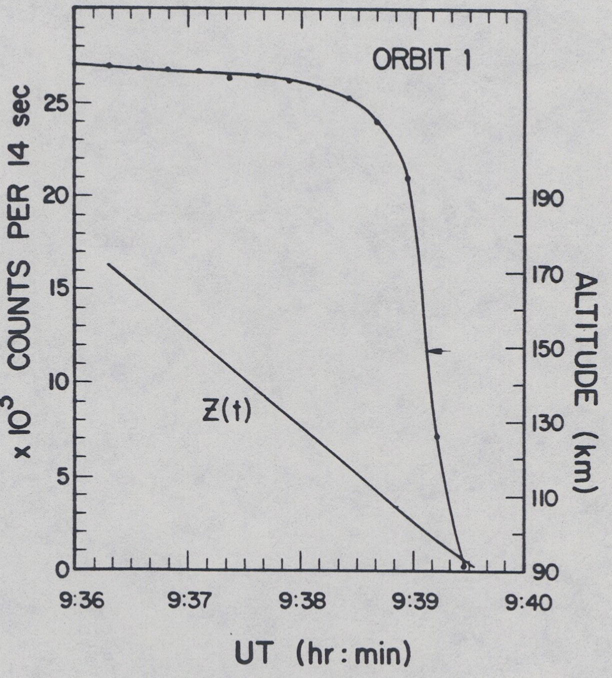

Figure 1. The variation of count rates as a function of the universal time for orbit 1. A temporary reduction in the count rate at 9^h37^m 22^s is due to guidance error. The variation of the tangent altitude during this observation is shown as a function of the universal time by the curve labeled Z(t). The minimum tangent altitude in this orbit was 50.9 km. The count rate at 100 km is marked with an arrow.

by H_2 absorption. The orbit 1 data were inverted by an iterative numerical technique (see Hays and Roble [1968] for the principle of the inversion of planetary occultation data.) The resultant O_2 densities are plotted as a function of height in Figure 3. The geographic latitude of the observations varied from 8.4°S (123 km) to 11.5°S (95 km). For comparison with the measurement, we also show in Figure 3 Jacchia [1971] model (900°K) O_2 density profile. The statistical errors in the measured densities based on one standard deviation fluctuation of the counting rates are less than ± 10% below 110 km. The error increases to ± 31% at 123 km due to continuously diminishing absorption beyond 110 km. The numerical inversion of orbit 1 data makes use of the ratio between the continuum count rate for orbit 1 and the count rate at a given height, so that the actual stellar photon flux does not enter the analysis. The value of the O_2 absorption cross section used in arriving at the number densities has been cited earlier. The O_2 absorption is then subtracted from the absorption measured in orbit 4. The inversion of the orbit 4 data assumes the line of sight optical depth in O_2 at a given height as deduced from the orbit 1 data, therefore, any uncertainty in the O_2 absorption cross section does not affect the derived H_2 densities. For thermal equilibrium relative population of H_2 in the observed J = 0 line at 1108.128Å varies from 17% at 95 km to 12% at 108 km due to variation in the temperature in this region of the atmosphere. The total H_2 density at a given altitude is obtained by the product of the H_2 density in the

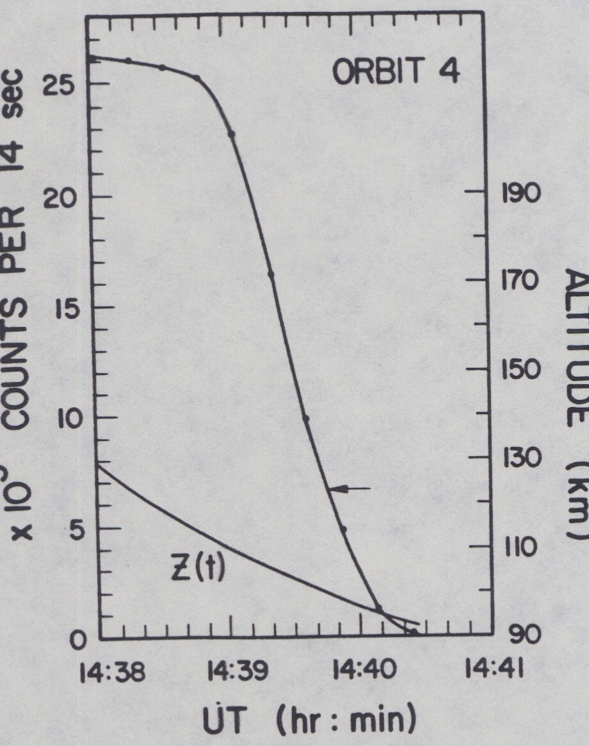

Figure 2. Same as Figure 1 except for orbit 4. The minimum tangent altitude in this orbit was 85.8 km.

J = 0 state and the partition function, which has the temperature dependence. The total H_2 densities obtained in this manner are plotted in Figure 4 for the various possible temperature profiles: 1966 U.S. Standard Atmosphere for the appropriate latitude of observation and the time of the year; for the OGO-6 λ5577 derived temperatures [Donahue and Carignan, 1975]; and for the Pitot tube measurements [Donahue and Carignan, 1975]. The geographic latitude of the observations varied from 14.3°S (108 km) to 17°S (95 km). For comparison with the measurements, we also show in Figure 4, Liu and Donahue [1974] theoretical models. The statistical errors of the measurements are shown by the error bars such that the negative error bar is placed on the lowest density while the positive error bar on the highest density at each altitude. The errors in the measured densities are insignificant over most of the altitude region. The rapidly vanishing optical depth in H_2 at 108 km gives rise to large statistical errors at and beyond this altitude.

DISCUSSION AND CONCLUSIONS

The agreement between the observed H_2 density profile and the model is so close that it is safe to conclude from the results of this experiment that the general features of the model are confirmed. There is abundant H_2 in the lower thermosphere and it is flowing upward in the manner expected. In Figure 4 we show predicted H_2 density profiles for two values of k_{23} - the so called high and low values of Liu and Donahue [1974a, b, c]

$$k_{23} = 1.3 \times 10^{-11} \exp(-330/T) \qquad (3)$$

$$k_{23} = 5 \times 10^{-12} \sqrt{T} \exp(-1000/T) \qquad (4)$$

with conditions otherwise the same as those described by these authors in their third paper. The upper curve is taken in fact from that paper and fits the observed density very well.

An increase in the mixing ratio of $2[H_2O] + 4[CH_4] + 2[H_2]$ in the stratosphere from 15 ppm, the value Liu and Donahue [1974c] assumed, by a factor lying between 1.6 and 2.3 would be needed to bring the predictions following from the low value of k_{23} into agreement with the observations. Mixing ratios for total hydrogen running between 24 and 35 ppm seem excessive. Furthermore, the combination of low k_{17} and low k_{23} predicts OH densities higher than those allowed by the single measurement of OH concentrations in the mesosphere by Anderson [1971] even when a mixing ratio of 15 ppm is assumed. Since the OH density varies roughly as the square root of the mixing ratio, this situation would become a good deal worse if the average total mixing ratio were increased by a factor of the order of 2. Of course this remark is based on a single OH observation. Ground based studies by Burnett [1976] show that the total amount of OH in the atmosphere is frequently larger than the amount predicted by models, even those using the low value for k_{17}.

If there are 15 ppm total hydrogen in the stratosphere, use of Table 4 of Liu and Donahue [1974a] shows that the combination of high k_{17} and high k_{23} calls for 4.3×10^7 H_2 molecules cm^{-3} at 100 km and the high low combination for 2.4×10^7 molecules cm^{-3}. This latter combination of rate constants would appear to call for unacceptably low concentrations of H_2. An increase in total hydrogen mixing ratio of the order of 16% would be enough to make the combination of high k_{17} and high k_{23} agree as well with the data as the low-high combination does for 15 ppm. Hence, these observations in themselves do not provide evidence supporting any particular value of k_{17} between $2 \times 10^{-11} cm^3 s^{-1}$ and $2 \times 10^{-10} cm^3 s^{-1}$. There is a growing body of evidence, however, that suggest the low value of k_{17} is close to the correct one. In any event, our observations tend to lend support for

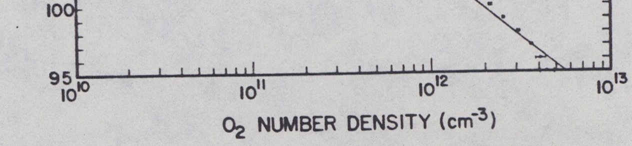

Figure 3. The measured O_2 densities and associated error bars. The Jacchia [1971] model (900°K) O_2 density profile is shown by the solid line curve.

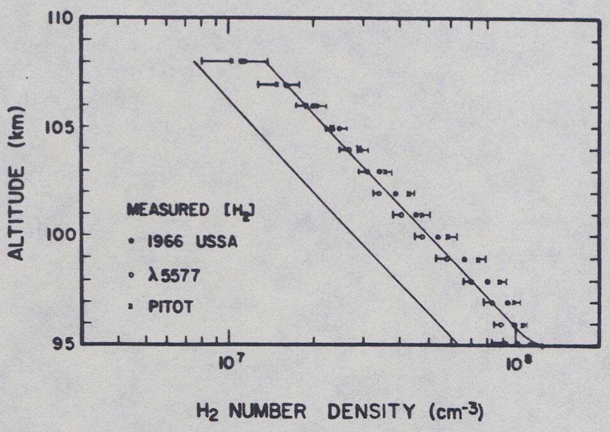

Figure 4. The H_2 densities as deduced from the inversion of the orbits 4 and 1 data. The densities are plotted for the various assumptions of the temperature profiles discussed in the text. The negative error bar is placed on the lowest H_2 density while the positive error bar on the highest density at each altitude. The range of Liu and Donahue [1974a, b, c] models, discussed in the text, is shown by the solid line curves.

the use of the higher value of k_{23} for the reaction of H and HO_2 that produces H_2.

The density of O_2 deduced from the observations is very interesting in the structure it exhibits. Generally, the values agree with the Jacchia [1971] model but suggest a temperature minimum near 105 km and a steeper gradient in temperature above 110 km. These are features exhibited by the Pitot tube measurements [Donahue and Carignan, 1975] discussed in connection with the analysis of the H_2 data. Note moreover, that the O_2 density profile obtained from the occultation data does not involve any assumptions concerning the atmospheric temperature.

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