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Measurements of exospheric hydrogen densities at a distance of 3 R_E (earth radii) are presented as a function of exospheric temperature. They imply that the density n_c at the exobase level decreases with exospheric temperature T_c but not enough to keep the Jeans escape flux F_J constant. The increase of F_J with exospheric temperature may be compensated for by the decrease of F_e, which measures the loss of hydrogen by charge exchange in the plasmasphere. The two fluxes would be equal to 6.6 × 10⁷ atoms cm⁻² s⁻¹ at a temperature T_c = 1070°K, giving a total escape flux in agreement with measurements of hydrogen compounds in the region from 30 to 50 km and theoretical mesospheric calculations.

The Lyman α intensity distribution of the geocorona was mapped in 1968 and 1969 from Ogo-5 with a resolution of 40 minutes of arc in a circular field-of-view of 30° around the earth-satellite line [*Bertaux and Blamont,* 1970]. A detailed analysis of these measurements, yielding exospheric H density and temperature determinations, was presented elsewhere [*Bertaux,* 1974].

In this paper we present an analysis of the variations of H density as a function of exospheric temperature and some implications concerning the H escape flux from the earth.

During the year extending from March 1968 to March 1969 the eccentric orbit of Ogo-5 (period of 2.5 days) changed little in celestial orientation, whereas a wide range of the sun-earth-satellite angle θ at apogee was covered (from 35° to 143°). Along each orbit a wide portion of the geocorona, often including both polar zones, was observed between 1.1 and 7 R_E (earth radii).

In order to derive H density determinations from Lyman α intensity measurements, several problems had to be overcome:

The first problem was substraction of the extrageocoronal Lyman α background (typically ≃6% of total Lyman α intensity for a line of sight located at 3 R_E from the center of the earth).

The second problem was multiple scattering in the geocorona (with a numerical method proposed by *Bertaux* [1974] and based upon radiative transfer calculations similar to *Thomas'* [1963]). This method takes care of the geometric conditions of observations.

The third problem was anisotropy of Lyman α resonance scattering [*Brandt and Chamberlain,* 1959]. Though this effect is weak, it shows up readily in the data if it is not taken into account, as a 6-month-period spurious modulation.

The fourth problem was fluctuations of the solar Lyman α intensity F_s at the center of the line. When Oso-5 measurements [*Vidal-Madjar et al.,* 1974] were not available for the date of Ogo-5 measurements, a statistical relationship between F_s and R_z (the Zurich sunspot number), valid for Oso-5 measurements, was assumed to hold.

Owing to the fact that the calibrations at Lyman α of Ogo-5 and Oso-5 instruments have been found consistent within 10%, we estimate at ±20% the absolute accuracy of [H] determinations and at ±10% the relative accuracy along 1 year of data.

The exospheric [H] distribution should be clearly related to the exospheric temperature. In order to study such a relationship we used the *Jacchia* [1971] exospheric temperature corrected for the geomagnetic effect. We present a correlation analysis for the density at R_E, where it was shown that the number of orbiting atoms (satellite particles) is negligible [*Bertaux,* 1974]. Each one of the 137 points of Figure 1 is representative of one orbit of data from Ogo-5.

For each orbit all the density measurements at 3 R_E were averaged together, a global estimate of the density over a period of 2.5 days thus being derived. The ordinate of each point of Figure 1 represents this density relative to a reference model, which contains 532 atoms cm⁻³ at 3 R_E.

The abscissa is the temperature T_{max} of the point at the exobase at which the temperature is maximum, according to Jacchia's procedure, for the time of the apogee of the orbit.

At the first glance the density at 3 R_E does not seem to depend strongly on the exospheric temperature. The statistical dependence indicated by a first-degree least squares fit (straight line of Figure 1) shows that a 10% variation of the exospheric temperature would statistically induce a variation of the density at 3 R_E less than ±4%, with a 0.95 degree of confidence.

We now compare these data with different hypothesis and theoretical models of the exosphere.

SPHERICAL MODEL OF CHAMBERLAIN

The simplest model is *Chamberlain*'s [1963] model; the H density is only a function of the radial distance r when the density n_c and temperature T_c, uniform over the exobase, are selected (no satellite particles are considered). We identify T_c with the mean exospheric temperature according to Jacchia:

$$T_c = \frac{1}{2}(T_{min} + T_{max}) \simeq \frac{1.15}{1.3} T_{max}$$

If the density n_c at the exobase level is constant when T_c (and T_{max}) varies, the density at 3 R_E increases as a function of T_{max} according to the curve marked CC on Figure 1. This curve passes through the center of gravity (open circle) of the cloud of data points for n_c = 7.5 × 10⁴ atoms cm⁻³.

In such a case the Jeans escape flux $F_J' = n_c V_e(T_c)$, where V_e is the effusion velocity at the exobase level, would increase rapidly with T_c (and T_{max}).

If the density n_c is adjusted to T_c in order to keep F_J' constant, at 3 R_E the density will decrease according to the curve

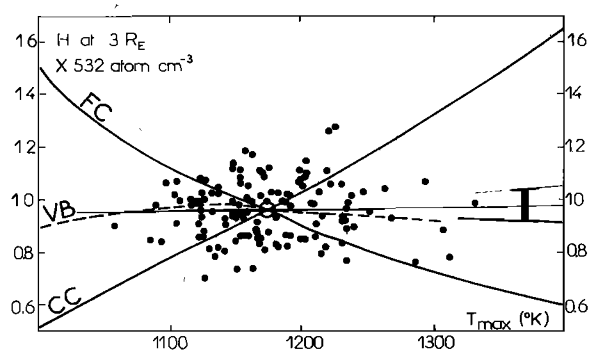

Fig. 1. Comparison of Ogo-5 experimental data to different theoretical assumptions. Each point represents a determination of the density of H at 3 R_E (ordinate) as a function of exospheric temperature T_{max} (abscissa). The center of gravity of the cloud of points (open circle) lies just below the density of 532 atoms cm^{-3}. The straight line, almost horizontal, is the least squares fit to the cloud of points. The error bar at the right indicates the 0.95 confidence interval for the slope of the straight line. The curve CC indicates the density variation at 3 R_E for a constant density at the exobase level, and the curve FC for a constant Jeans flux at the exobase level. The dashed curve marked VB is extracted from Oso-5 data. Both Ogo-5 and Oso-5 data indicate that the Jeans escape flux increases with exospheric temperature.

marked FC on Figure 1. Neither of these two assumptions (constant density or constant flux) is validated by the data; indeed the density at the exobase decreases with T_{max} but not enough to keep the flux F_J constant. The Jeans escape flux F_J' increases with the exospheric temperature.

The density n_c that would keep constant the density at 3 R_E (on the least squares fit to the data points) is indicated in Table 1 as a function of T_{max} or T_c. Then the Jeans escape flux can be evaluated with $F_J' = n_c V_e(T_c)$ and is indicated in Table 1, as well as on the upper solid curve of Figure 2.

ASPHERICAL EXOSPHERE

We have also used a model with an axial symmetry in which the density and temperature at the exobase level vary sinusoidally between the points (T_{max}, n_{min}) and (T_{min}, n_{max}). In addition, we assume that the ratio n_{max}/n_{min} adjusts itself to the zero net ballistic flux condition at the exobase, in which case it satisfies the relationship [*Quessette*, 1972]

$$\frac{n_{max}}{n_{min}} = 0.15 + 0.67 \times 10^4 \frac{\Delta T}{\bar{T}^2}$$

in which $\Delta T = T_{max} - T_{min}$ and $\bar{T} = \frac{1}{2}(T_{max} + T_{min})$. With Jacchia's relationship $T_{max} = 1.3 T_{min}$ (only approximate when there is some geomagnetic activity), it becomes

$$\frac{n_{max}}{n_{min}} = 0.15 + \frac{0.197 \times 10^4}{T_{max}}$$

Measurements of *Vidal-Madjar et al.* [1974] on Oso-5 provided a verification that this relationship holds, at least on a statistical basis. They also provided a statistical relationship between n_{min} and the exospheric temperature T_{max} that we took into account in our exobase model (Table 1); then both distributions of density and temperature at the exobase level are completely defined as a function of T_{max}, as well as the exospheric density distribution, which can be computed by following the method of *Vidal-Madjar and Bertaux* [1972]. By excluding the satellite particles and averaging over the whole sphere a mean density at 3 R_E as a function of T_{max} is obtained, which is related to the Oso-5 results. The dashed curve of Figure 1 and marked VB represent the result of this exercise after multiplication by a factor of 1.06 to place the curve at the center of gravity of the Ogo-5 points.

The excellent agreement in absolute value between the Ogo-5 densities measured at 3 R_E and the densities derived from Oso-5 density measurements at the exobase level is a favorable indication concerning the coherence of Ogo-5 and Oso-5 data; it also indicates that the relative number of satellite particles at 3 R_E is not very important. More relevant to the present study is the fact that the slope of curve VB is very small and agrees much better with Ogo-5 data points than curves FC or CC.

Then the observed variation (or absence of variation) of the exospheric density at 3 R_E as a function of the exospheric temperature implies a certain statistical relationship between the exobase density and the exospheric temperature. Such a relationship is already present in the Oso-5 measurements [*Vidal-Madjar et al.*, 1974]; however, Oso-5 measurements concern a limited region of the sunlit exobase (±30° of latitude), whereas the Ogo-5 measurements at 3 R_E concern the whole exobase.

With the data of Table 1 and the above-described exobase model the escape flux at the 500-km level was integrated and averaged over the whole exobase, and its variation as a function of T_{max} is indicated by the upper dashed line of Figure 2. It is nearly identical to the flux computed with the simple spherical model.

As the distribution of particles just below the exobase is not

TABLE 1. The Exospheric Temperature is Characterized Either by the Maximum Temperature T_{max} or by a Mean Temperature T_c

	T_{max}				
	1000°K	1100°K	1200°K	1300°K	1400°K
T_c, °K	884	973	1061	1150	1238
n_{min}, atoms cm^{-3}	8.7×10^4	6.8×10^4	5.1×10^4	4.0×10^4	3.6×10^4
n_{max}/n_{min}	2.12	1.94	1.79	1.66	1.56
n_c, atoms cm^{-3}	1.41×10^5	9.4×10^4	7.15×10^4	5.5×10^4	4.4×10^4
$n_c H_c$, atoms cm^{-2}	1.25×10^{13}	9.2×10^{12}	7.6×10^{12}	6.38×10^{12}	5.5×10^{12}
$F_e = 2kn_cH_c$, atoms cm^{-2} s^{-1}	1.07×10^8	7.9×10^7	6.5×10^7	5.5×10^7	4.7×10^7
$F_J = F_J' \times 0.73$, atoms cm^{-2} s^{-1}	4×10^7	5.1×10^7	6.7×10^7	8.3×10^7	10×10^7
$F_e + F_J$, atoms cm^{-2} s^{-1}	1.47×10^8	1.3×10^8	1.32×10^8	1.38×10^8	1.47×10^8

The density n_{min} is taken from Oso-5 measurements; n_c is the density (in a spherical model) that gives a constant density at 3 R_E; the charge exchange mechanism results in a flux F_e, proportional to n_c and the scale height H_c; F_J is the corrected flux for Jeans escape.

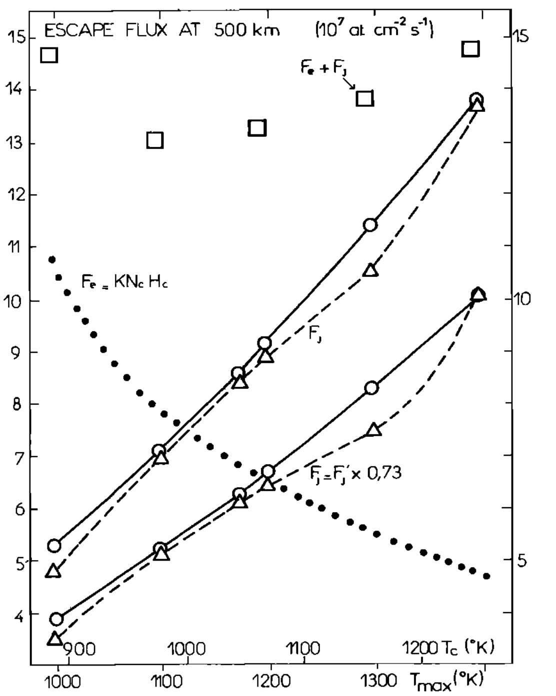

Fig. 2. The Jeans escape flux F_J, estimated either with a spherical model (open circles) or with a model with axial symmetry (triangles), increases with exospheric temperature. The flux F_e, due to charge exchange with protons, is assumed to be proportional to n_cH_c (dotted line). The total flux $F_e + F_J$ (squares) is nearly constant in the explored temperature range.

strictly a Maxwell-Boltzmann distribution, the real escape flux is somewhat reduced. A corrective factor of 0.73 [*Chamberlain and Campbell,* 1967; *Brinkmann,* 1971] has been included in the lower curves of Figure 2, and they serve as a basis for the following discussion.

DISCUSSION

Whatever exospheric model is taken to evaluate the Jeans escape flux $F_J = 0.73F_J'$ from Ogo-5 density measurements, we find that F_J increases substantially with the exospheric temperature (or solar activity). Coupled with the assumption that F_J is equal only to the diffusion flux of atomic H at 100 km [*Kockarts and Nicolet,* 1962], this fact is in complete contradiction with two recent theoretical works concerning the H photochemistry of the mesosphere between 30 and 100 km [*Hunten and Strobel,* 1974; *Liu and Donahue,* 1974]. The main conclusion of these studies is that the value of the diffusion flux F_{100} of H in all forms at 100 km is quite insensitive to the details of chemical reactions, to the eddy diffusion coefficient, and to the solar flux variations; F_{100} is found to be mainly proportional to the mixing ratio of the element H (present in H_2O, CH_4, and H_2) at 30 km, with a value $F_{100} = 1.5 \times 10^8$ atoms cm^{-2} s^{-1} for the value of H mixing ratio derived from [H_2O], [CH_4], and [H_2] measurements in the lower mesosphere. This value of F_{100} is at least 2 times higher than the value of F_J derived from Ogo-5 for an exospheric temperature $T_{max} = 1200$°K, a second discrepancy thus being created. This discrepancy can be overcome only if we reject the assumption that the thermal (or Jeans) escape rate is equal to the diffusion flux F_{100}; an important part of the H atoms (under the form H or H_2) that cross upward of the 100-km level must escape by mechanisms other than thermal escape.

This idea was already suggested independently by *Tinsley* [1974], *Liu and Donahue* [1974], and *Bertaux* [1974]. The most efficient escape mechanisms are: (1) charge exchange of H in ballistic orbits with H^+ in the plasmasphere, the velocity of the new neutral being, most of the time, higher than the local escape velocity [*Cole,* 1966; *Tinsley,* 1973, 1974] and (2) polar wind in high magnetic latitude regions [*Banks and Holzer,* 1968].

A rough estimate of the fluxes at 500 km averaged over the whole exobase induced by mechanisms 1 and 2, respectively, is 2×10^8 and 10^7 atoms cm^{-2} s^{-1}. It is clear that they may well be as important as Jeans escape, if not more important.

The dependence of these mechanisms on the exospheric temperature has been investigated by *Liu and Donahue* [1974]. A rough estimate of the amount of neutral H available for charge exchange is given by the quantity $2n_cH_c$, where H_c is the scale height of H as a function of T_c at the exobase level, and is indicated in Table 1 with the values of n_c determined from the Ogo-5 data at 3 R_E (the factor of 2 in the expression $2n_cH_c$ allows approximately for the nonexponential behavior of the H distribution). This quantity decreases with exospheric temperature; then there is a possible compensation between Jeans escape and charge exchange. If we assume that the escape flux F_e corresponding to the charge exchange is only proportional to the quantity $2n_cH_c$,

$$F_e = 2kn_cH_c$$

we can compute from the data of Table 1 a value of k that would give the same flux $F_e + F_J$ for $T_{max} = 1000$° and 1400°K. It is $k = 4.3 \times 10^{-6}$ s^{-1}.

The physical meaning of k is that the quantity $2n_cH_c$ would decrease to $1/e$ of the original value in the time $k^{-1} = 2.3 \times 10^5$ s if charge exchange was the only loss process.

Then the flux F_e can be computed between 1000° and 1400°K, as well as the sum $F_e + F_J$, indicated in Table 1 and Figure 2.

The absolute value of $F_e + F_J$ is in very good agreement with the flux $F_{100} = 1.5 \times 10^8$ atoms cm^{-2} s^{-1} derived from mesospheric calculations and H compound measurements between 30 and 50 km [*Hunten and Strobel,* 1974].

With these measurements and the Ogo-5 data we arrive at the very simple following picture concerning the total escape flux of H averaged over the surface of the earth:

1. The sum of Jeans escape flux and charge exchange flux is equal to the flux of the element H in atomic and molecular form [*Tinsley,* 1969] at 100 km and is constant with exospheric temperature (at least in the range 1000 → 1400°K for T_{max}).

2. When the exospheric temperature increases from T_c = 880 to T_c = 1240°K, the Jeans escape flux increases from 4×10^7 to 10×10^7 atoms cm^{-2} s^{-1}, whereas the charge exchange flux, proportional to the quantity n_cH_c, decreases from 1.1×10^8 to 4.7×10^7 atoms cm^{-2} s^{-1}. The two fluxes are equal for $T_c \simeq 1070$°K.

A further refinement of this picture would include the polar wind; however, in this range of temperature its contribution (averaged over the whole exobase) is small and only slightly varying with temperature [*Liu and Donahue,* 1974]. The slight departure of $F_e + F_J$ from a constant value at both ends of the explored temperature range could also be due to the assumption that charge exchange is only proportional to the quantity $2n_cH_c$; large exospheric temperature changes are likely to be associated with solar activity changes, which can influence greatly the ion temperature and concentration in the plasmasphere and subsequently the efficiency of charge exchange.

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