JOVIAN UPPER ATMOSPHERIC TEMPERATURE MEASUREMENT BY THE VOYAGER 1 UV SPECTROMETER

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Abstract. The first measurement of the neutral temperature in the exosphere of Jupiter is reported. The observations were carried out by the Voyager 1 Ultraviolet Spectrometer during the solar occultation phase beginning 4.5 hours after the Jupiter encounter. The range of the exospheric temperature is found to be $1450 \begin{smallmatrix}+300\\-250\end{smallmatrix}$ K. The uncertainty in the determination of the temperature appears to be largely a consequence of the lack of knowledge of the brightness distribution on the solar disc at the time of the observations. The high exospheric temperature appears to result from a combination of upward propagating inertia gravity waves, magnetospheric soft electrons and auroral electrons including those from the Io-plasma torus.

INTRODUCTION

The Voyager 1 spacecraft swung behind the planet Jupiter on March 5, 1979 and entered the solar occultation zone at approximately 1600 UT. For the next two hours, the Voyager Ultraviolet Spectrometer (UVS) measured the absorption of the incoming solar radiation in the range 500–1700Å as this radiation penetrated the atmosphere of Jupiter. A complete spectrum was taken every 0.32 sec. The experiment was successful during ingress. During exit however, the Sun was not centered on the spectrometer slit, as a consequence of which the signal was low and statistics quite poor. This paper describes the results obtained during the entry solar occultation experiment.

The solar occultation experiment is a relative experiment in the sense that it is independent of the absolute flux of the source. The unattenuated count rate of the source (Sun) at a given wavelength is measured before it is absorbed in the atmosphere. As absorption by an atmospheric gas takes place, the count rate begins to diminish. It is the ratio between the unattenuated and attenuated flux which determines the line of sight column density of the absorbing column of gas. Knowing the nature of the absorber, its absorption characteristics as a function of wavelength and the geometrical path of absorption one can, in principle determine the density and scale height of the absorber. Other details of the Voyager UVS instrument and the solar occultation experiment may be found in our earlier papers (*Broadfoot, et al.*, 1977 and 1979). The angular diameter of the Sun as viewed from Jupiter is approximately 0.1°. The range at which the occultation experiment was carried out is about 7R_J. Therefore, the effective size of the Sun in the atmosphere of Jupiter is about 800 km. Although the tangential velocity of the spacecraft at this time was approximately 20 km s^{-1} the size of the Sun is by far the overriding factor in determining the effective height resolution. It is therefore not quite straightforward to determine the atmospheric structure from the abovementioned solar occultation experiment since the highest scale height may never even approach the effective height resolution. It is, however, possible to effectively eliminate the size of the Sun from the analysis if we are dealing with a uniform source of radiation in the selected wavelength region and if the absorption data at several wavelengths were simultaneously obtained. The important point to note is that the Sun need be uniform only in the adjacent channels or sets of channels selected. The analysis is further facilitated if only single absorbing species were present. The atmosphere well above the homopause is expected to contain H_2 as the major gas, therefore the assumption of a single absorber is valid in that height regime. Indeed, an examination of the photoabsorption spectrum of H_2 reveals that most of the relevant radiation will be absorbed out beyond about 1000 km above the cloud tops. The information on the H_2-scale height, and hence the exospheric temperature can therefore be retrieved from the data relevant to the region of the H_2 absorption as discussed below. Considering the energy sinks and sources in the upper atmosphere of Jupiter, it is reasonable to expect a constant temperature, hence constant scale height for the exosphere, although it is not a prerequisite for the analysis discussed below. We will also discuss the consequences to our results of non-uniform distribution of intensity over the disc of the Sun.

DATA ANALYSIS

The basic method of the analysis illustrated below is to derive scale height information from a consideration of the altitudes where near unity (and equal) optical depths at two wavelengths with different cross sections of an absorbing species occur. Consider for instance two wavelengths λ_1 and λ_2 at which a single atmospheric gas absorbs the incoming solar radiation. The unattenuated fluxes at the top are given by $Io]\lambda_1$ and $Io]\lambda_2$; whereas the fluxes at some heights corresponding to the depths of penetration of wavelengths λ_1 and λ_2 are given by $Iz]\lambda_1$ and $Iz]\lambda_2$. The relationship between Io and Iz is given by the following Beer's law:

$$Iz]\lambda_1 = Io]\lambda_1 \exp(-\tau_1) \qquad (1)$$

and,

$$Iz]\lambda_2 = Io]\lambda_2 \exp(-\tau_2) \qquad (2)$$

where, τ_1 and τ_2 are the optical depths at wavelengths λ_1 and λ_2 for the abovementioned heights.

If we have equal amounts of absorption at the two wavelengths, i.e.

$$\text{if} \quad Iz/Io]\lambda_1 = Iz/Io]\lambda_2 \qquad (3)$$

then it follows from (1) and (2) that

$$\tau_1 = \tau_2 \qquad (4)$$

$$\text{while, } \tau_1 = N_1 \, \eta_{h1} \, \sigma_1 \qquad (5)$$

$$\text{and } \tau_2 = N_2 \, \eta_{h2} \, \sigma_2 \qquad (6)$$

where, N represents the vertical column density of the absorber, and

η_h = horizontal air-mass factor (*Hunten*, 1971)

σ = absorption cross section of the gas at a given wavelength

Also, $\eta_h = \sqrt{2\pi R/H}$, (*Hunten*, 1971) (7)
where, R = planetocentric distance of the absorbing layer

H = scale height of the absorber

$\pi = 3.14159$

If the cross sections at the two wavelengths selected were not drastically different from each other, so that $\Delta z \ll H$; and if H were assumed constant in the exosphere over a small height range, one would find that

$$\eta_{h1} \approx \eta_{h2} \qquad (8)$$

With this approximation, one finds from expressions (4), (5) and (6) that

$$N_1/N_2 = \sigma_2/\sigma_1 \qquad (9)$$

The vertical column density ratio can also be expressed by:

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$$N_2 = N_1 \exp(-\Delta z/H) \tag{10}$$

where Δz refers to the difference between the depths of penetration of λ_1 and λ_2. If Io for the two wavelengths are determined at the same instant of time, and if the interval between the times at which same optical depth at λ_1 and λ_2 is reached is Δt, then

$$\Delta z = v\Delta t \tag{11}$$

where v is the rate of change of the tangent ray height in the atmosphere determined from the spacecraft attitude data.

One can therefore determine the scale height using expressions (9) and (10), i.e.

$$H = \Delta z/\ln(\sigma_2/\sigma_1) \tag{12}$$

For an isothermal upper atmosphere, the temperature will then be given by

$$T = H\frac{mg}{k} \tag{13}$$

where k = Boltzmann constant

g = acceleration due to gravity for the latitude and height of observation

m = mean molecular weight; m = 2 AMU in the exosphere where H_2 is the major gas.

For the purpose of illustration we show in Figure 1 an unattenuated solar spectrum as viewed by the UVS, and its absorption in the Jovian atmosphere a little while later. The photoabsorption cross section curve for H_2 for the wavelength range relevant to the UVS observations is shown in Figure 2. The ideal portion of the spectrum for analyzing the atmospheric absorption data lies between 500Å and 800Å, the region where the cross section changes gradually. The variation in the cross section above 800Å is quite rapid. Considering the relatively large rate of change of tangent ray height and the large projected size of the Sun on the spectrometer slit, we find the data in the region beyond 800Å as unsuitable for ascertaining the H_2 scale height with this analysis. For this analysis we have grouped the data from the spectrometer to simulate data produced by a multichannel photometer. This simplifies the analysis procedure but yields neither the detailed information nor the confidence about the lower atmosphere ultimately available from a treatment of the full set of spectrometric data; and restricts the results to the region well above the homopause where scale heights are large and the complications of multiple absorbers not applicable. The photometer simulation for the exosphere is justified by its expediency and by the fact that the photometer bandpasses have been carefully chosen to minimize the instrumental effects not considered in this analysis. Since the Sun maps on to about 30Å in the UVS we have summed the data in several sets of three adjacent channels in various parts of the absorption spectrum. We have selected those wavelength ranges in which an examination of the data showed that the intensity profiles were well behaved. A representation is shown in Figure 3 and the details are listed in Table 1. Our analysis indicates that the combinations of sets (i) 1 and 2, (ii) 3 and 1, and (iii) 4 and 3 are ideally suited for determining the exospheric scale height. The combinations of sets 1 and 4, and 2 and 4 are not suited since the H_2 absorption cross section gradient changes sign on either side of 700Å. The combination of sets 2 and 3 is unsuitable since the H_2 absorption cross section in these sets is about equal. These last sets however provide a useful information. The difference in the depths of penetration of these last two sets determines the accuracy with which we are able to measure the relative heights. This difference turns out to be about 20 km, much less than the exospheric scale height. The results of calculation based on expression (12) for the appropriate sets are given in the last column of Table 1. The exospheric scale height lies between 250 and 370 km, or $H = 300^{+70}_{-50}$ km. This translates into an exospheric temperature in the range 1450^{+300}_{-250} K. The equatorial value of g (*Smoluchowski*, 1976) was assumed since the observations were for that region; g was further adjusted for the tangent ray height of the absorber above the cloud tops. Considering a relatively low value of eddy diffusion coefficient at the homopause, i.e. $K \approx 3 \times 10^5$ cm²s⁻¹ as implied by the Voyager 1 ionospheric data (*Atreya et al.*, 1979) and the UVS airglow data (*Broadfoot et al.*, 1979), we find that the amount of absorption shown in Table 1 takes place at about 1500–2000 km above the ammonia cloud tops in the relevant wavelength ranges.

Discussion

The results presented in this paper represent the first measurement of the 'neutral' temperature in the Jovian atmosphere, although plasma temperatures in the ionosphere have been previously measured by the radio occultation technique. The calculations are found to be independent of the number of channels summed in a given set so long as the portion of the spectrum analyzed meets the criterion discussed in the previous section. The single most disconcerting uncertainty in our analysis arises from the lack of knowledge of the distribution of brightness on the solar disc in the relevant wavelength region. Because of the spatial non-uniformity of the Sun at EUV wavelengths (*Reeves and Parkinson*, 1970) it is probable that large areas of the solar disc are more intense by factors of two or three than the average intensity of the disc. If the spatial brightness distributions in the wavelengths used in this analysis are different so that there is a separation between the 'centers of gravity' of the intensity distributions between the two wavelengths λ_1 and λ_2, this separation is directly translated into an altitude shift between the two light curves, $I\lambda_1$ and $I\lambda_2$. We believe that the uncertainty in our determination of the exospheric temperature can be attributed largely to the assumption of uniform intensity on the solar disc. Because of irregular and unsystematic changes in the solar disc intensity, it is not advisable to extrapolate from any previous EUV observations of the Sun.

In this short paper we can only briefly discuss the possible mechanisms for the heating of the Jovian exosphere. The internal heat source is responsible for Jupiter's radiating more than twice the amount of energy it receives from the Sun (*Aumann et al.*, 1969). Radiative equilibrium considerations including this excess energy yield an upper stratospheric/mesospheric temperature of ~ 170K as has been confirmed observationally by Voyager (*Hanel et al.*, 1979) and Pioneer (see review by *Hunten*, 1976) instruments. The propagation and subsequent dissipation of inertia gravity waves is an important likely mechanism for the thermospheric heating as has been proposed

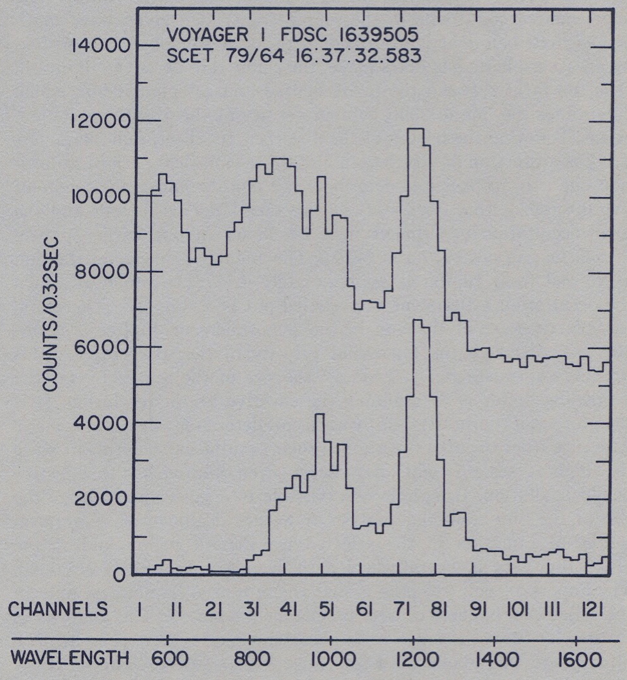

Figure 1. Unattenuated solar spectrum in the 500–1700Å range as viewed by the Voyager 1 UV Spectrometer (upper curve), and after it begins to get absorbed by the Jovian atmosphere (lower curve). The zero for the upper spectrum is offset by 5000 counts.

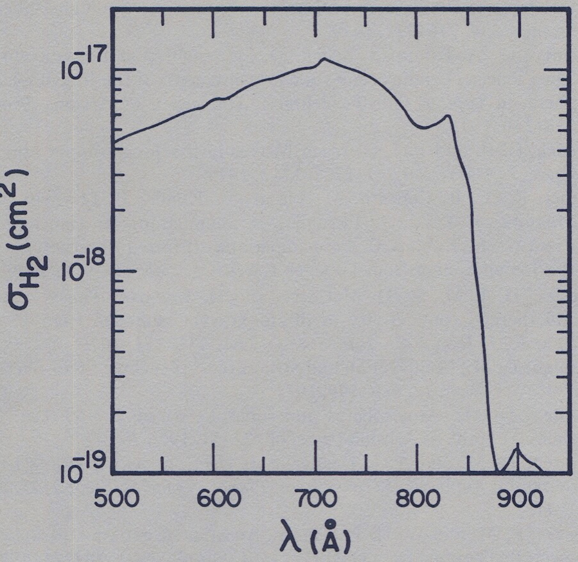

Figure 2. Photoabsorption cross section curve for H_2.

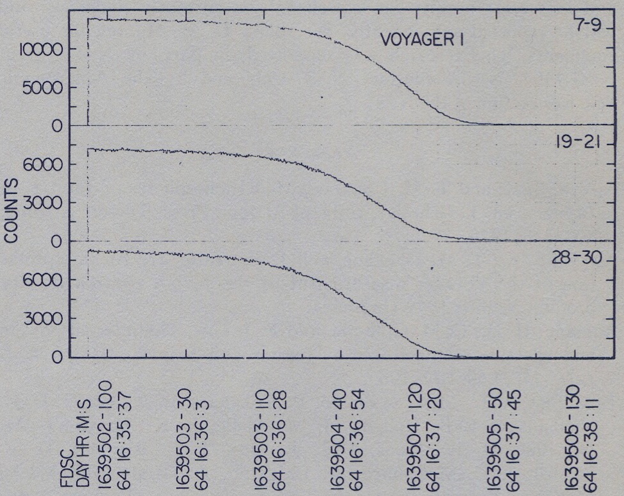

Figure 3. Counting rate in three representative sets of channels: 7–9 (590–618Å), 19–21 (665–692Å), and 28–30 (702–729Å) as a function of time during the solar occultation.

by *French and Gierasch* (1974) and quantitatively discussed by *Atreya and Donahue* (1976). Using the estimates of the flux of energy carried by the gravity waves, the high temperature approximation of the H_2 thermal conductivity and a simplified heat conduction equation, we find the Jovian exospheric temperature by use of the following expression from *Hunten and Dessler* (1976):

$$\kappa \frac{dT}{dz} = F \qquad (14)$$

$$\text{where } \kappa = AT^s \qquad (15)$$

$$\text{therefore } \; T_{ex}^{s+1} = T_m^{s+1} + (s+1)\frac{F}{A}\Delta z \qquad (16)$$

In the above expressions, T_{ex} and T_m are the exospheric and mesopause temperatures respectively. T_m is taken to be 170K (*Hanel et al.*, 1979; *Hunten*, 1976.) The parameters in the thermal conductivity κ (in erg $cm^{-1}s^{-1}K^{-1}$) for H_2 at high temperatures in the exosphere of Jupiter have the following values:

$s = 0.751$, and $A = 252$ (*Hanley et al.* 1970)

and the flux associated with the inertia gravity waves, F is approximately 3 ergs $cm^{-2}s^{-1}$. The waves generally breakup and deposit their energy about five to ten scale heights above the mesopause, i.e. Δz in expression (16) lies between about 125 km and 250 km. With the values of the parameters given here, we find

$$T_{ex} = 1260 \text{ K for } \Delta z = 125 \text{ km}$$

$$\text{and } T_{ex} = 1855 \text{ K for } \Delta z = 250 \text{ km}$$

The range of exospheric temperatures calculated in this manner is consistent with the observations. Thus it appears that the inertia gravity wave source alone may be capable of supplying sufficient heating to explain the observed exospheric temperature on Jupiter.

Another important source of thermospheric heating has been proposed by *Hunten and Dessler* (1976). They suggest that heating could result from the precipitation of soft electrons from a warm plasma. The ionospheric electrons could be energized to about 10 eV by energy transferred from Jupiter's fast spin, with further increase in energy provided by an abiabatic acceleration driven by atmospheric winds. It has been well established that the Jovian exospheric temperature has increased by about 50% from the time of Pioneer 10 and 11 observations (*Fjeldbo et al.* 1976, *Hunten* 1976) to the time of Voyager 1 encounter of Jupiter (*Eshleman et al.* 1979, *Atreya et al.* 1979, and this paper). It is however, not apparent if this change is indeed linked to a change in solar activity although it is a tempting assumption to make. Although the inertia gravity wave 'source strength' is unlikely to vary with the solar activity, the ultimate energy dissipation in the form of heat could be a strong function of the atmospheric turbulence or mixing. The mixing parameter, eddy diffusion coefficient has definitely decreased by more than two orders of magnitude since the Pioneer Jupiter flybys (see a discussion in *Broadfoot et al.*, 1979; and *Atreya et al.*, 1979). It is also likely that the inertia gravity wave source serves as a major but constant underlying energy source superimposed on which is a magnetospheric soft electron or auroral electron (including Io plasma torus) source of thermospheric heating which could vary with the solar activity.

The analysis presented in this paper is preliminary. A more thorough analysis involving a complete simulation of the entire entry

TABLE 1. Entry Solar Occultation, Day 64:1979

Set number, (i)	Channels summed	Wavelength range, $\Delta\lambda$ (Å)	Average $\sigma(H_2)$ in $\Delta\lambda$ (cm^2)	Io (Counts)	Iz (Counts)	Iz/Io	t_o UT (hr:min:sec)	t_z UT (hr:min:sec)	$\Delta t = t_z - t_o$ (sec)	H (km)	Remarks: Set Combination
1	7,8,9	590–618	6.90×10^{-18}	13,900	10,326	0.7428	16:35:37.0	16:36:55.56	78.56	302	1 & 3
2	15,16,17	665–692	9.88×10^{-18}	7,500	5,572	0.7428	16:35:37.0	16:36:49.06	72.06	371	2 & 1
3	19,20,21	702–729	1.00×10^{-17}	7,020	5,215	0.7428	16:35:37.0	16:36:50.1	73.1	251	3 & 4
4	28,29,30	785–813	6.07×10^{-18}	8,220	6,106	0.7428	16:35:37.0	16:36:44.0	67.0		

and exit solar occultation experiments is currently underway and will be reported subsequently. We thank D. M. Hunten for useful comments. This research was supported, in part, by NASA grant NSG-7404, NASA contract NAS7-100; and by the Atmospheric Sciences section of the NSF.

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