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POLARIZATION MEASUREMENTS OF THE FAR ULTRAVIOLET DAY AIRGLOW

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ABSTRACT

The intensity and polarization of the OI, 1304Å and 1355Å multiplets and the Vegard-Kaplan System of N_2 have been measured in the dayglow up to 200 km at 90° to the incident solar radiation. No polarization was observed. The lack of observed polarization of OI, 1355Å and the N_2, Vegard-Kaplan system is proof of collisional excitation. Comparison of the observed intensities of OI, 1355Å and the N_2, VK system with recent theoretical predictions for photoelectron excitation show excellent agreement for OI but the N_2, VK emission is 10 times weaker than predicted. The volume emission rate of N_2, VK is observed to follow the N_2 density above 165 km.

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INTRODUCTION

The production of the dayglow is dependent upon the sun as an energy source. This energy input results in the production of radiations which are the result of resonant and fluorescent scattering, photochemical reactions, and the collisional excitation of atoms and molecules by ions and photoelectrons. The radiation comprising the dayglow is characterized by the two quantities, intensity and polarization, which are determined by the physical processes producing the dayglow.

On the atomic scale radiation is normally polarized whereas on the macroscopic scale this is not necessarily the case. For single resonant or fluorescent scattering the polarization or anisotropy of the scattered radiation results from the interaction of an anisotropic light source incident on an isotropic medium. The solar radiation is anisotropic in that there are no vibrations of the electric vector in the direction of propagation. The incident sunlight is absorbed by those atoms or molecules which have a certain orientation with respect to the incident beam. The resonance scattering of linearly polarized light results from the excitation of those levels where the magnetic quantum number M remains constant ($\Delta M = 0$). This can produce a preferential population of the magnetic sub levels of the excited state. The emitted radiation may be characterized by both π and σ components where $\Delta M = 0, \pm 1$ respectively. If the sums,

I_π and I_σ, of the π and σ components are unequal then the radiation is polarized. The linear polarization at 90° to the solar rays is

$$P = \frac{I_\pi - I_\sigma}{I_\pi + I_\sigma} \qquad (1)$$

If the excitation is by sunlight then the polarization, P_n, at 90° to the incident radiation is related to Equation 1 for the resonant scattering of linearly polarized light by

$$P_n = \frac{P}{2 - P} \qquad (2)$$

A general discussion of the polarized emission of radiation is given in the works of Mitchell and Zemansky (1934) and Feofilov (1961).

Unpolarized radiation is produced by the isotropic excitation of a medium. Consequently multiple resonant and fluorescent scattering, and collisional excitation such as that produced by photoelectrons leads to unpolarized light. A measurement of the polarization of the far ultraviolet dayglow can determine whether the excitation is due to single resonant or fluorescent scattering (anisotropic), or multiple scattering or collisional excitation (isotropic).

INSTRUMENTATION

The far ultraviolet polarization analyzer which has been described in detail by Heath (1968) consists of a light baffle, a rotating transmission pile-of-plates analyzer, a filter wheel, and an EMR, 542G photomultiplier (CsI cathode) with its associated electronics. The baffle and the analyzer aperture limit the field of view to 4.0° (0.39×10^{-2} sterad). The analyzer consists of eight cleaved plates of LiF which were set at Brewsters angle for hydrogen Lyman - α. Each of the five filter wheel positions were interposed for three seconds during which time the analyzer rotated through 720°. The five positions contained, respectively, no filter, CaF_2, BaF_2, Al_2O_3 and a blank. Combining the "solar blindness" of the CsI photocathode with the short wavelength transmission limits of the filters made it possible to measure currents produced by the radiation in the regions from 1200-2000Å, 1230-2000Å, 1335-2000Å, 1435-2000Å, and the dark current. The signal currents were presented as a telemetry voltage by a four-decade, linear, range-switching electrometer. Subtractive techniques were used to isolate the radiation in the wavelength intervals 1435-2000Å, 1335-1435Å, 1230-1335Å, and 1200-1230Å. In the reduction of the data it was assumed that the principal dayglow features from 1200-1435Å are those reported from the spectrophotometric measurements of Fastie et al. (1964), and that the radiation from 1435-2000Å is due to the Vegard-Kaplan system, A $^3\Sigma_u^+$ - X $^1\Sigma_g^+$, and the Lyman-Birge-Hopfield system $a^1\Pi_g$ - X' Σ_g^+, of N_2. The assumed principal emissions of the dayglow in the region from 1200-1435Å are the following: hydrogen Lyman-α $1s\,^2P$ - $2p\,^2P$ at 1215Å, the OI multiplets $2p^4\ ^3P$ - $3s\,^3S$ at 1302-06Å, and $2p^4\ ^3P$ - $3s\,^5S$ at 1355-58Å.

The measurements of the relative intensities are accurate to ± 2-3%, while the absolute intensities which were obtained by calibration against a NO ionization cell in conjunction with a sodium salicylate coated photomultiplier are thought to be accurate to ±15%. The exception to the above is the OI multiplet at 1355Å because its intensity is derived from subtracting two comparable signals; hence, the accuracy is probably two to three times worse.

The polarization analyzer was carried to an altitude of 200 km aboard on Aerobee 150 rocket which was fired from White Sands, New Mexico, at 0820 MST on August 29, 1966. At launch the 3-hour geomagnetic planetary index was $K_p = 2$ while during the previous period the index was $K_p = 4$, which marked the end of 5 quiet days. The value of the 10.7 cm solar flux was 130 for August 29th. Inospheric soundings taken at White Sands at 0815 and 0830 MST gave monotonically increasing electron densities with altitude which ranged from 1×10^5 cm^{-3} at about 120 km to 4×10^5 cm^{-3} at 200 km. A cylindrical electrostatic probe aboard the rocket measured electron densities and temperatures during the flight which ranged from 3×10^5 cm^{-3} at 120 km to 4.3×10^5 cm^{-3} at 200 km. These values represent a mean as large local fluctuations were observed during the flight according to Findlay (1968).

An inertial attitude control system was used to orient the rocket as is shown in the zenith-azimuth angle plot of the polarization analyzer view in Figure 1. The solar zenith angle was 58° and its azimuth was 100° at the initiation of the flight. The geomagnetic field at WSMR is at 60° elevation and at 192.5° azimuth.

While all systems aboard the rocket functioned properly the tracking radars lost the vehicle at $t = 186$ sec, and they were unable to reacquire the rocket until $t = 456$ sec at which time the recovery chute had deployed. It was possible to match the performance at all times for which radar data existed by another Aerobee flight which carried a payload of the same weight. This was used to derive the altitude data.

OBSERVATIONS

The effect of scattered light was observed on all measurements recorded prior to $t = 234$ sec which corresponded to solar illumination of the photometer axis at angles less than 80°. Prior to 225 sec all photometer signals exhibited polarization resulting from sunlight scattering off the baffle. Consequently measurements are presented only for those times for which there appears to be no contamination by scattered light, i.e., $t \geq 238$ sec. From times $t = 238$ to 391 sec no evidence of any polarized emission was observed. At $t = 400$ sec a small degree of polarization ($\sim 16\%$) was observed in the range of 1425-2000Å which is attributed to Rayleigh scattering at about 80 km.

The results for H, Lyman - α have been published by Heath (1967). For OI, the altitude profiles of the 1304Å resonance transition are shown in Figure 2, and those for the 1355Å transition are given in Figure 3. The analysis by Barth (1965) of the intensity distribution of the Vegard-Kaplan system of N_2 excited by photoelectron impact has made it possible to assign an intensity scale to the

Vegard-Kaplan emission of N_2 shown in Figure 4. All data points indicated by circles shown in Figures 2-4 were recorded at a zenith angle of 65° and an azimuth of 351°. The triangular data points refer to different zenith angles. A summary of this observed horizon brightening for H, OI, and N_2 is presented in Table 1. In all cases the observed horizon brightening is less than the simple geometrical factor given by the ratio of the secants of the two angles.

No polarized emission was observed at 90° to the sun and the terrestial magnetic field from apogee (200 km) to less than 100 km on the down leg of the flight. Consequently the best one can do is to establish an upper limit on the possible degree of polarization based on an analysis of the telemetry records and the characteristics of the polarization analyzer. This is given in Table 2 along with the theoretical values for single resonance scattering at 90° to the sun for the multiplets and transitions observed as derived from the formulas of Feofilov (1961). The effect of hyperfine structure has not been included. A discussion of the magnitude of this effect for Lyman α is given by Brandt and Chamberlain (1960).

DISCUSSION

There are two principal sources which are responsible for the excitation of the far ultraviolet dayglow. These are the resonant or fluorescent scattering of sunlight and the collisional excitation by photoelectrons. A third possibility recently proposed by Kondo and Kupperian (1967) for a possible source for

Lyman - α at high altitudes and latitudes is the excitation by collisions between neutral hydrogen atoms and the charged particles in the radiation belts. Donahue (1967), however, maintains that the measurement of Lyman - α polarization and horizon brightening are consistent with a hydrogen atmosphere normalized to 3×10^7 atoms/cm^3 at 100 km. The radiative transport problem for the 1304Å resonance radiation has been treated by Donahue and Fastie (1963), and Donahue (1965).

The recent calculations by Green and Barth (1967) on the photoelectron excitation of the dayglow make it possible to compare the theoretical predictions with observations. In the spectral range from 1200-2000Å the features of the dayglow which should be excited primarily by photoelectron excitation and not the resonance scattering of sunlight are the 1355Å multiplet of OI and the Vegard-Kaplan and Lyman-Birge-Hopfield systems of N_2. This comparison can be made by determining the factor, α, which when multiplied by the density (cm^{-3}) or the integrated column density (cm^{-2}) gives the volume emission rate (cm^{-3} sec^{-1}) or the column emission rate (cm^{-2} sec^{-1}). The curves given by Green and Barth (1967) indicate that a column density of 5.8×10^{16} cm^{-2} of O atoms above 150 km leads to a column emission rate of 6.9×10^8 quanta/cm^2 where $\alpha_{GB}(1355) = 1.2 \times 10^{-8}$ quanta/atom. In this work the observed column emission rate of 5.7×10^8 quanta/cm^2 (corrected to zenith) corresponds to 4.8×10^{16} cm^{-2} O atoms above 150 km which is based on model 4 of the Cospar International

Reference Atmosphere (1965) for 8 hours local time and F = 125. Hence

α_{Obs} (1355) = $1.2 \times 10^{-8} \frac{\text{quanta}}{\text{atom}}$ which agrees very well with the calculated value.

The emission of the Vegard-Kaplan and Lyman-Birge-Hopfield systems of N_2 should contribute most of the radiation which produces the signal in the photometer sensitive from 1435-2000Å. An estimate of the relative contributions of the VK and the LBH systems can be made from the curves given by Green and Barth (1967) and the tables of the product of the Franck-Condon factor and the albedo for single fluorescent scattering, Barth (1965). If collisional deactivation is neglected I_{VK}/I_{LBH} = 8.4 while the relative strength of the VK bands to the LBH bands seen by the photometer is 1.18. Consequently the photometer with maximum sensitivity at 1600Å sees I_{VK}/I_{LBH} = 10. Thus the volume emission rate given in Figure 5 is due primarily to the VK bands.

The N_2 densities given in Figure 5 by the solid curve labeled 18.05 gives the densities measured by the Thermosphere Probe by Spencer et al. (1967) on August 26, 1966 at 1331 hours (F = 130) from Wallops Island. These measured densities were corrected to the local time of the White Sands launch. Also included for reference are the N_2 densities listed for model 4 (F = 125) for 0800 hours MST of CIRA (1965).

Using the measured N_2 densities in Figure 5 and the volume emission rates one has $\alpha_{Obs}(VK) = 2.6 \times 10^{-8}$ quanto/mol. in the region where the volume emission rate parallels the N_2 density. From the curves given by Green and Barth (1967) assuming no collisional deactivation of the VK system one has $\alpha_{GB}(VK) = 2 \times 10^{-7}$ quanta/molecule which is approximately an order of magnitude larger than the observations indicate.

If one assumes that the photometer channel at 1600Å records principally the VK emission one can set an upper limit on the ratio of the collisional deactivation coefficient to the transition probability of A $^3\Sigma_u^+$ state of N_2. The failure of the volume emission rate to track the N_2 density below 165 km shows that collisional deactivation is important for depopulating the A state of N_2. The rate of depopulation of an excited state is

$$\frac{dn^*}{dt} = An^* + \sum_x n^* n_x k_x \tag{3}$$

where A is the Einstein coefficient for radiation, n^* is the density of the excited species, n_x is the density of the quenching species, k_x is the quenching coefficient, and x represents a particular quenching species. The fraction of radiation emitted by a collisionally quenched state is

$$F = \frac{1}{1 + \frac{1}{A} \sum_x n_x k_x} \tag{4}$$

According to the review article by Hunten and McElroy (1966) O and O_2 are the principal species producing the quenching of the A state of N_2. Using the O and O_2 densities of model 4 of CIRA (1965) with the observation that F (165 km) = 0.9 from Figure 5 one can write

$$A(A\,^3\Sigma_u^+) = 8.3 \times 10^{10}\ \mathrm{cm}^{-3}\ k_o + 1.8 \times 10^{10}\ \mathrm{cm}^{-3}\ k_{o_2} \tag{5}$$

Consequently, given the collisional deactivation coefficients one can determine the radiative transition probability and vice versa.

CONCLUSIONS

The observation that there was no detectable polarization of the far ultraviolet dayglow at 90° to the sun is an indication that the excitation is not by single resonant or fluorescent scattering, but by either multiple resonance scattering (OI, 1304A) or photoelectron excitation (OI, 1304Å and 1355Å, and N_2, VK). In the case of the N_2, VK and OI, 1356Å emission the lack of observable polarization is conclusive proof that one is observing photoelectron excitation and not Rayleigh scattering which is polarized. Agreement with the calculations by Green and Barth (1967) on the intensity of the photoelectron excited dayglow is excellent for OI, 1355Å but the observed N_2, VK emission is about 10 times smaller than the calculated intensity. Also the collisional deactivation of the A-state of N_2 is negligible above 165 km. Furthermore a simple photomultiplier with a CsI photocathode and an Al_2O_3 window could be used to measure N_2 densities above 165 km in the photoelectron excited dayglow.

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Table 1

Horizon Brightening Observed at Apogee

Transition	Zenith angle (θ)	Time (sec)	Horizon brightening obs.	Horizon brightening $\frac{\sec 65°}{\sec \theta}$
H, $1s\ ^2P - 2p\ ^2P$	32°	242	1.37	2.00
OI, $2p^4\ ^3P - 3s\ ^5S$	29.5°	238	1.14	2.06
N_2, $A\ ^3\Sigma_u^+ - X\ ^1\Sigma_g^+$	46°	248	1.43	1.63
			1.33*	

*Value derived from extrapolation of signal at zenith angle 65° to altitude of 46° measurement.

Table 2

Observed Upper Limit of Far Ultraviolet Dayglow Polarization

Species	Transition	J	Wavelength (Å)	Polarization (Theory)	Polarization Observational Upper Limit*
H	1s ^2S - 2p ^2P	1/2-3/2	1215	0.428	0.015
		1/2-1/2	1215	0	
OI	$2p^4$ ^3P - 3s ^3S	2-1	1302	0.0073	0.007
		1-1	1304	0.198	
		0-1	1306	1.00	
	$2p^4$ ^3P - 3s ^5S	2-2	1355	0.287	0.04
			1358	0.287	
N_2	$A\ ^3\Sigma_u^+ - X\ ^1\Sigma_g^+$	$\Delta J = +1$[a]	[d]	0.077	0.01
		$\Delta J = -1$[b]		0.077	
		$\Delta J = 0$[c]		0.333	

[d] Vegard-Kaplan observed in region 1435-2000Å

*For total multiplet

[a] From 1.0 to 0.077 for increasing J (R-branch)

[b] From 0 to 0.077 for increasing J (P-branch)

[c] From 0 to 0.333 for increasing J (Q-branch)

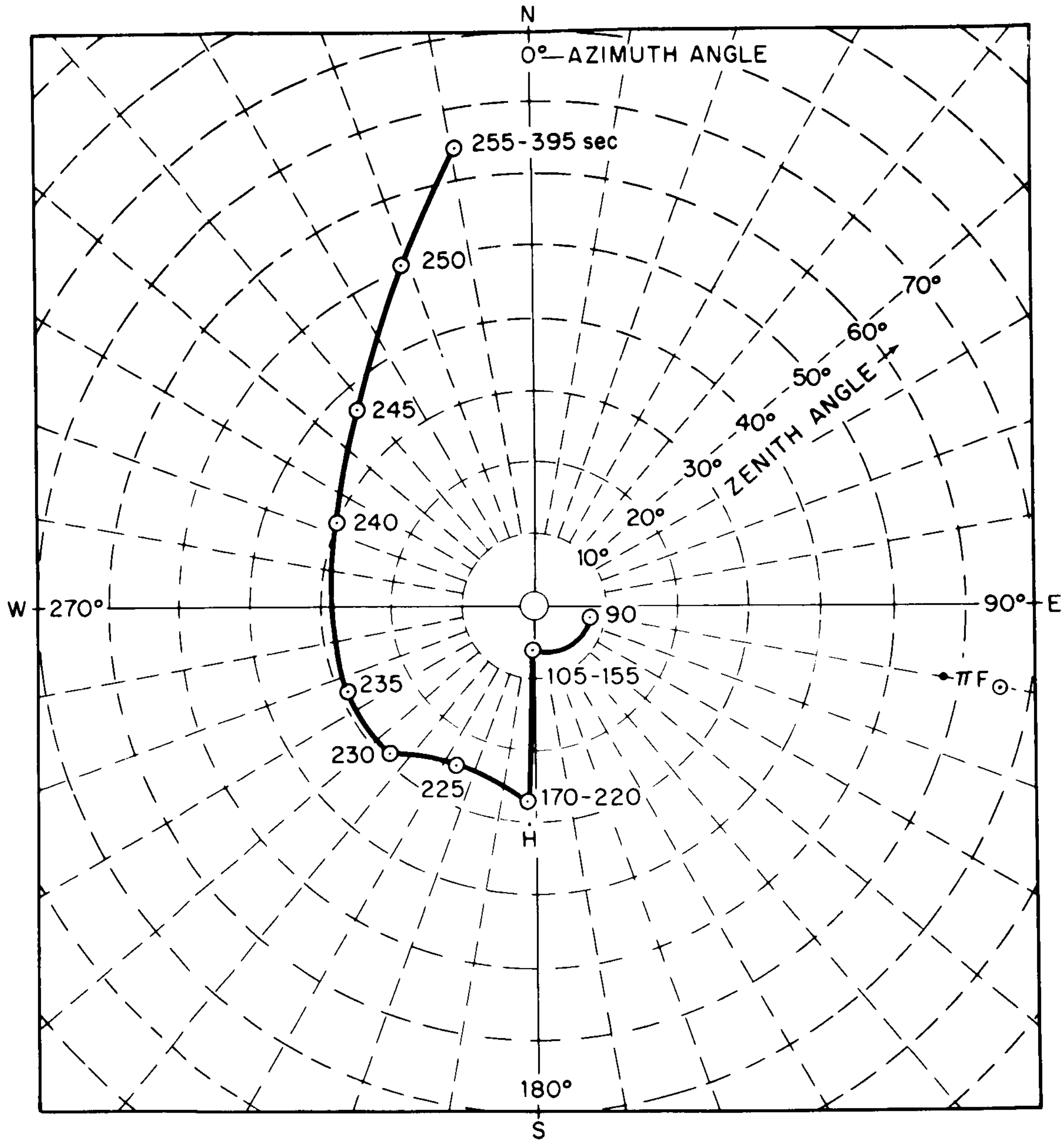

Figure 1. Zenith-azimuth Angle Plot of the Polarization Analyzer Axis During Flight

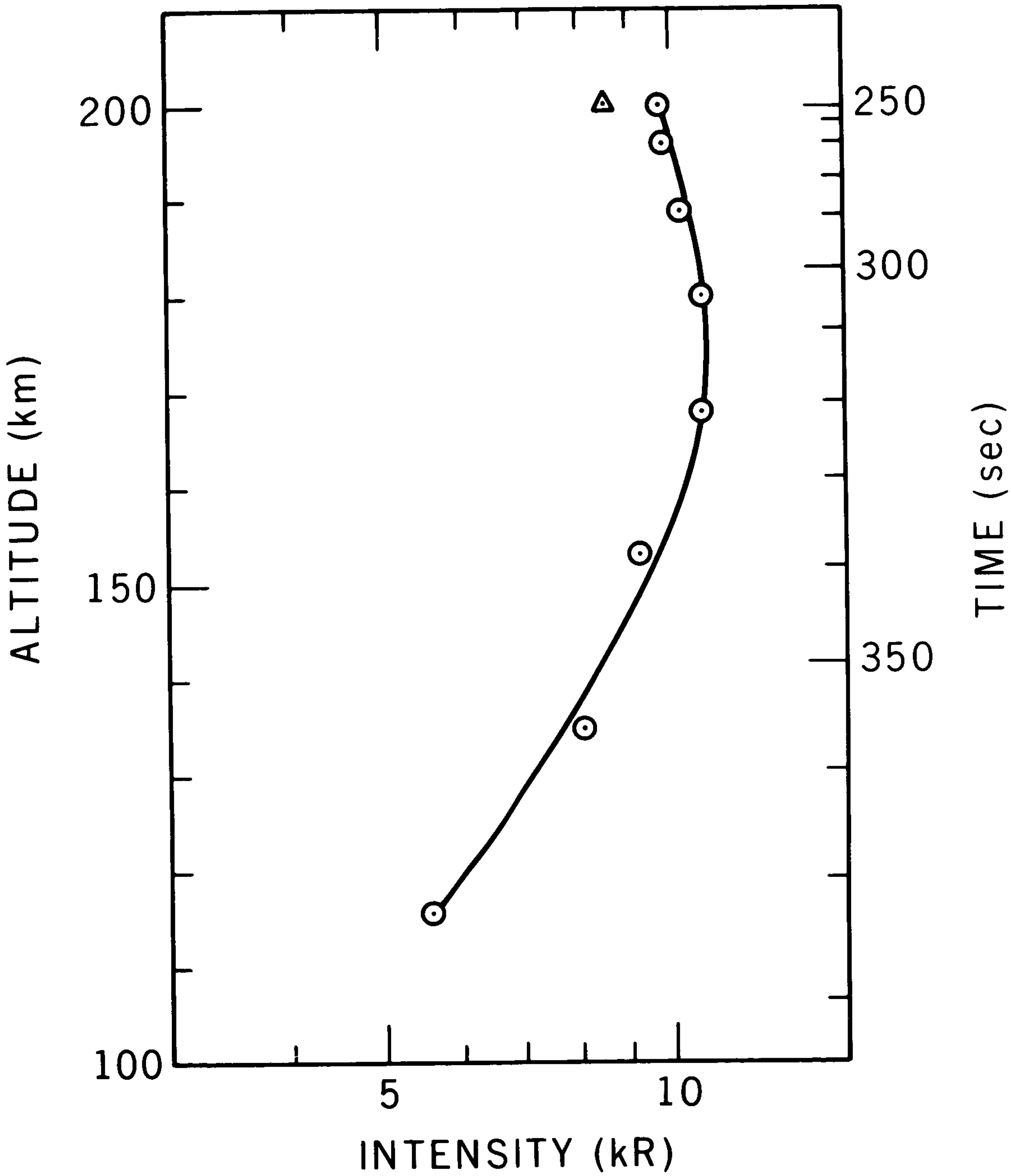

Figure 2. Intensity of OI, 1304Å Multiplet. ⊙- data Points Taken at Zenith Angle 65° and Azimuth 351°. △ - Indicates Horizon Brightening.

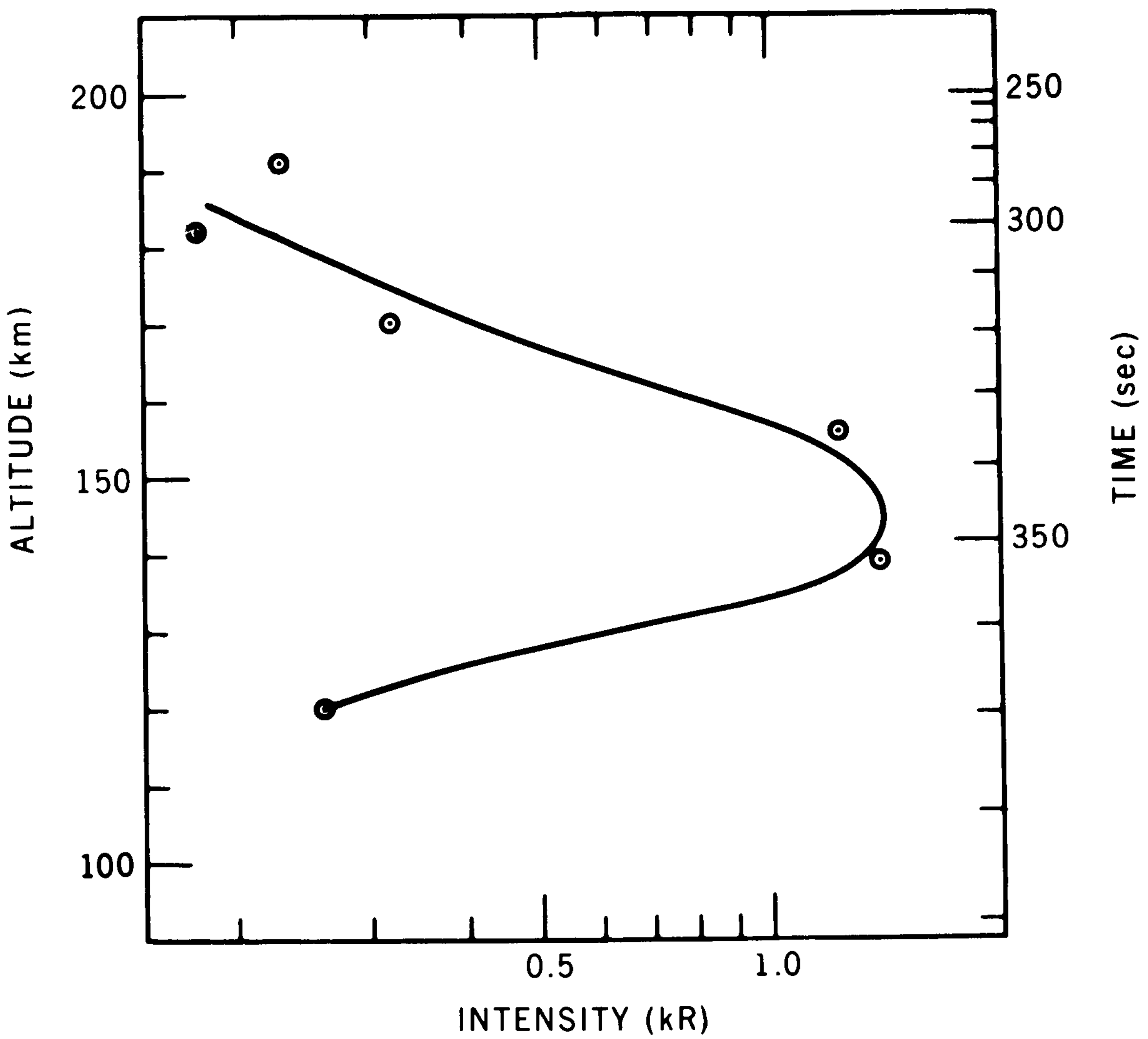

Figure 3. Intensity of OI, 1355Å Multiplet at Zenith Angle 65° and Azimuth 351°.

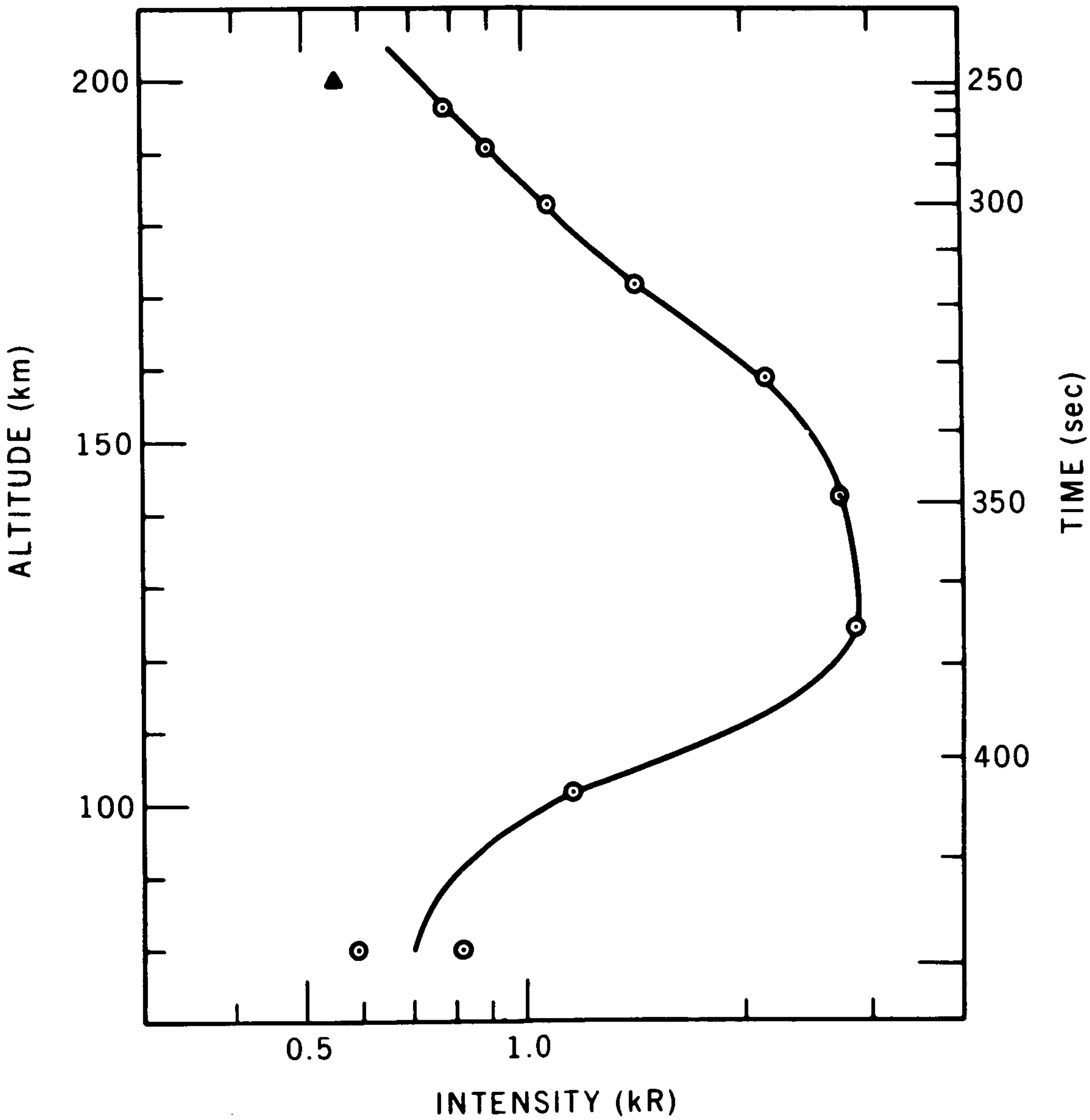

Figure 4. Intensity of N_2, Vegard-Kaplan System. ʘ-Data Points Taken At Zenith Angle 65° and Azimuth 351°. △-Indicates Horizon Brightening.

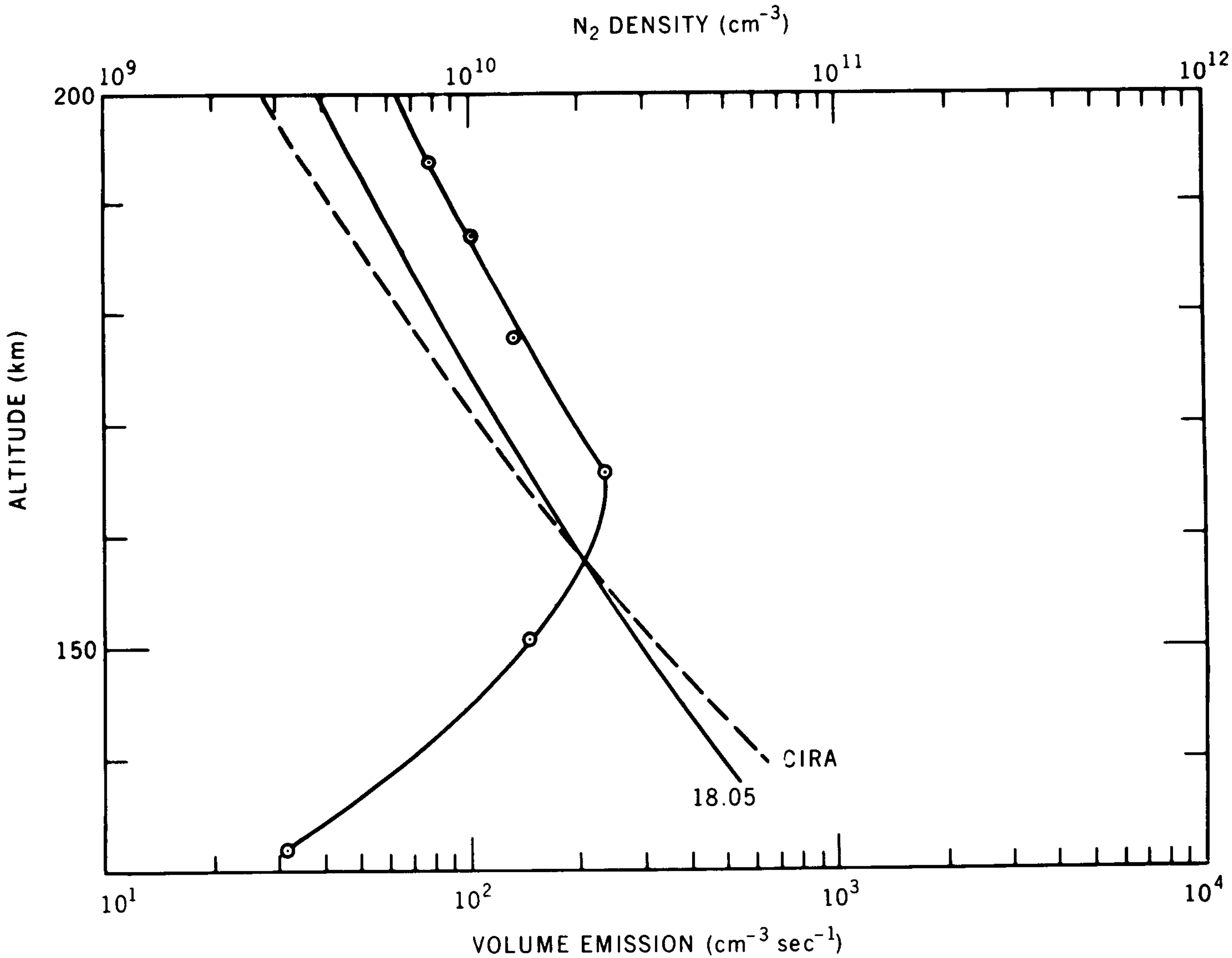

Figure 5. Volume emission rate of N_2, Vegard-Kaplan system. N_2 densities measured by Spencer et al. (1967) with Thermosphere Probe (18.05). Model atmosphere N_2 density (CIRA).