A MEASUREMENT OF THE ULTRAVIOLET NIGHTGLOW SPECTRUM

by

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ABSTRACT

The spectrum of the ultraviolet night airglow from 2300-3800A has been recorded with 12A resolution by a fast spectrograph carried on an Aerobee rocket launched from White Sands Missile Range, New Mexico at 0615 UT 1 Dec. 1964. All of the features observed can be attributed to the molecular oxygen Herzberg band system ($A^3\Sigma_u^+ \rightarrow X^3\Sigma_g^-$) with the exceptions of the OI transauroral line at 2972A and five unidentified bands, all lying at wavelengths greater than 3400A. The Herzberg 7,0 band at 2519A marks the shortest wavelength emission feature and no emission from upper states with $v' > 7$ is observed. The total zenith emission rate in the wavelength interval photographed is roughly estimated as 600R. Details of the spectrograph are described and a comparison of the nightglow spectrum with published laboratory afterglow and ground observed nightglow spectra is made.

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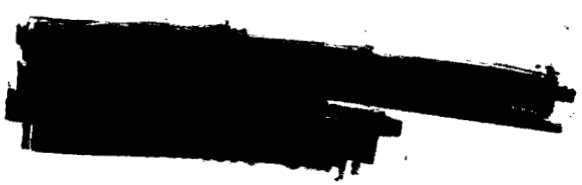

INTRODUCTION

The ultraviolet night airglow was conclusively identified ten years ago as arising almost entirely from the Herzberg system of molecular oxygen (Chamberlain, 1955). Since then other ground based spectrograms (for instance Yarin, 1961; 1962) have been obtained which repeat the same results. The nightglow spectral region below the atmospheric cut off at about 3100A has, until this year, been recorded only by broad band photoelectric radiometers carried in sounding rockets. These rocket results (Dunkelman, Boggess, and Scolnik, private communication, 1959; Packer, 1961) gave approximate zenith emission rates of 0.2 - 0.3 R/A for the spectral region from 2500 - 2800A, which may be compared with ground based estimates in the observable region of about 0.9 R/A (Yarin 1961, 1962). The radiometer bandpasses, as shall be seen, extended below the limit of the Herzberg emission and thus gave rather low average emission rates. Very recently Stecher (1965) obtained a scan of the nightglow horizon with a rocket-borne objective grating spectrometer. The low resolution energy distribution derived from his data gives about 0.7 R/A throughout the region 2500-3500A.

The desire to extend the airglow spectral analysis below 3100A, the improvement in film spectrographic techniques and rocket control systems, and the results of the rocket-borne radiometers encouraged us to attempt to record the faint nightglow spectrum with a fast spectrograph during a relatively short rocket flight. By controlling the rocket's attitude the spectrograph could be kept pointed at the horizon where the enhanced emission is some 50-60 times more intense than at the zenith (or nadir). The resulting decrease in exposure time required to produce a photographic spectrum also decreases the zodiacal light and integrated star light background to a negligible level.

THE EXPERIMENT

Since airglow emission rates are relatively low, exposure times from rockets are short, and payload space is small, a fast and compact spectrograph was called for to record the ultraviolet nightglow spectrum. The final spectrograph design consisted of a novel, off-axis, cylindrical parabolic optical collimator; a 10 cm plane grating with 2160 lines/mm ruling; a 40 mm aperture, f/0.7 Schmidt camera; and an unusual film transport mechanism. The optical design of the spectrograph was developed by D. C. Evans and A. Boggess III in our laboratory.

Figure 1 is a schematic of the overall spectrograph. The collimator consists of one quadrant of an f/0.9 cylindrical parabola. The focal length is 220 mm and the useful diameter 12 mm. With an entrance slit of 0.55 mm width a beam collimated to within 0.2 degrees is produced. Because of the nature of the source being photographed (the edge-on horizon airglow) and the limitations on the rocket pointing capabilities the entrance slit could not be oriented parallel to the horizon but had to be kept perpendicular to the airglow layer.

The Schmidt cameras and film transports were developed by the Perkin-Elmer Corporation, Norwalk, Conn. and have been used both as imaging cameras and in objective grating spectrographs for planetary observations (Evans, 1965) in addition to this work. The camera 40 mm diameter corrector lens may be made of either CaF_2 or fused silica. The MgF_2 overcoated primary mirror has a diameter of 65 mm and a focal length of 28 mm. Both the camera and the film transport have venting arrangements for outgassing during the rocket ascent. The camera has a total aperture ratio of T/0.9 including obscuration losses.

The film transport is detailed in Figure 2. It contains 6 film planchets at the end of a spoked wheel which, when electrically actuated, successively positions each of the film discs in the focal plane of the Schmidt camera by a spring driven ratchet (the Schmidt optical system is also [illegible] in Figure 2). The [illegible] consist of 17 mm

diameter film discs conformed to 25 mm radius glass discs by mechanical pressure. The film transport section is removed from the optics for loading of film and manual winding.

The spot image formed of a collimated beam by this camera is less than 0.10 mm in diameter corresponding to less than $1/4^{o}$ angular resolution. Achieving good focus across the entire film plate has required careful adjustment of each planchet for proper position in all three axes.

Eastman spectroscopic film types I-O and 103 a0 have been used in the camera plus Kodak Pathe' type SC-5 film. The fragile SC-5 which is extremely sensitive to pressure marking and contamination, has very successfully withstood deformation to the 25 mm radius film planchet surface.

Two spectrographs, one CaF_2 and one fused silica, and a conventional imaging camera for aspect data were mounted in an attitude controlled NASA Aerobee, 4.83 launched from White Sands Missile Range, New Mexico at 2315 MST on 30 Nov. 1964. The GSFC Attitude Control System was used with the addition of a sequenced program which kept the horizon fixed in the spectrograph field within approximately $\pm$ 2 degrees throughout the flight. A single 260 sec exposure was taken during the flight, which reached an apogee of 184 km. Eastman type 103a0 film was used with development for 9 min. in D-19 developer. In addition to the airglow spectra recorded, some very interesting photographs of the earth's night horizon and nightglow layer were obtained by the aspect camera. These results are being published separately (Hennes and Dunkelman, 1965).

RESULTS

Figure 3 is a photograph of the ultraviolet nightglow spectrum with an approximate wavelength scale super-imposed. The horizon image is smeared in the vertical direction by the rocket motion during the flight. Although the film was sensitive to below 2300A no features were recorded below 2500A.

Figure 4 is a densitometer trace of the film shown in Figure 3. The heavy black line marks the film density which would be produced by exposure to a 0.75 R/A source under the conditions of the flight exposure. It is thus both a crude measure of the absolute zenith emission rate of the nightglow at the time of the exposure and a measure of the instrument spectral sensitivity (including spectrograph transmission and film sensitivity). The spectrograph entrance slits were set as wide as the limiting Schmidt camera optics would permit. The resulting image spot size (line width) corresponded to about 12A and is shown in the figure as slit width.

Figure 5 is the corrected ultraviolet nightglow spectrum. The background fog, film characteristic response and instrument spectral sensitivity have been removed from the film data and the result displayed on a scale linear in both wavelength and emission rate. The instrument relative response was measured by means of an N.B.S. calibrated tungsten-iodine source at the longer wavelengths and by a sodium salicylate coated phototube at the shorter wavelengths. Over 2200 points were taken from the densitometer trace, converted to corrected linear data by a computer program, and replotted to make up this spectrum which is the best representation of the ultraviolet nightglow which can be obtained from our data.

Based on the emission rate ordinate used in Figure 5 the total zenith emission rate from the spectral region included is approximately 600R. The emission rate has been arrived at by two independent means. A pre-flight laboratory calibration of the spectrograph and flight emulsion was made using an extended source of Hg 2537A radiation. For a four minute exposure the sensitivity at 2537A required 30 [illegible] to produce a film density 1.0. During the flight the spec[illegible] viewed the horizon where the edge-on intensity smeared by the rocket motion, is some 35 times the zenith intensity as

determined by the visible sensitive aspect camera in the same payload (Hennes and Dunkelman, 1965). The equivalent zenith emission rate necessary for the horizon to produce a film density 1.0 should therefore be 0.85 R/A.

A second estimate of emission rate has been made based on the observed OI green line zenith emission rate of 145R at the time of the flight. Dr. June Jones of Geo-Science, Inc. Alamorgordo, New Mexico has kindly supplied this number from the set of continuous readings made at the airglow observatory on Sacramento Peak. Using the ratio of 16:1 for the rate coefficients of the 5577A green lines, $O(^1S) \rightarrow O(^1D)$ and the 2972A trans-auroral line, $O(^1S) \rightarrow O(^3P)$ we have a 9R zenith emission rate at 2972A (Garstang, 1951). The effective slit width makes this equivalent to 0.75 R/A at 2972 A. Unfortunately, the 2972 atomic line falls next to the Herzberg 7, 4 band at 2976A and both sit on the long wavelength portion of the 5,3 band at 2945A. Reconstructions of these three features indicate that anywhere from 20-30% of the total emission between 2924 - 2989A could come from the 2972A atomic line. Since the effect of increased horizon smearing is to raise the equivalent zenith emission rate and the effect of a larger ratio for the 5577A/2972A intensities is to lower the rate the somewhat arbitrary choice of 0.75 R/A was made to produce a spectrogram density of 1_e0 at 3000A in Figure 4. The uncertainty in this number must be about 50%.

Table I gives the approximate integrated zenith emission rate for the spectrum of Figure 5 between the wavelength intervals indicated. The various Herzberg bands in each region are listed. In addition to the molecular bands the OI atomic line at 2972A and five unidentified bands, marked by X, in the longer wavelength region are included. These unidentified bands occur at wavelengths of about 3430, 3507, 3615, 3698, and 3789A and their position

is indicated by the short bars in Figure 5. These features were noted by Chamberlain (1955) in his nightglow spectrum but remain unexplained. The bands at 3615A (the large deformation on the short wave side of the 4,7 band) and 3698A (the entire band at 3700A) are the most prominent. All other features in Figure 5 can be attributed to one or more of the Herzberg bands.

The intensities of the individual bands can only be determined for the short wavelength portion of the spectrum where the band overlap is small. For these features where only two bands overlap, such as the 7,2 and 4,1 systems at 2732A and 2750 respectively, an estimate of the intensity in each has been made by a graphical reconstruction of the two bands using 12A resolution and fitting the results to the observed spectral shape. The results of such a reconstruction are only approximate of course. Table II gives the estimated intensities for as many features as can be measured or reconstructed from Figure 5.

CONCLUSIONS

The Herzberg band system of O_2, $A^3\Sigma_u^+ \rightarrow X^3\Sigma_g^-$, was observed in considerable detail in the laboratory oxygen afterglow work of Broida and Gaydon (1954) and has been the subject of detailed calculations by Pillow (1953 a, b). The by now classical work of Broida and Gaydon assigned the proper vibrational numbering system to the Herzberg transitions and permitted eye estimates of intensity. Bands from upper states with v' of 9 or 10 were observed in their laboratory emissions but are not found in the night sky.

The total intensity of the ultraviolet nightglow is not large and over half of the emission is in the ground observable region of the spectrum. Chamberlain (1961, p. 538) suggested that a considerable fraction of the total Herzberg system in the night sky might be in the middle

ultraviolet but this is clearly not the case. This conjecture is based on the method of excitation proposed as a three-body recombination

$$O + O + M \rightarrow O_2(A^3\Sigma_u^+) + M.$$

The expected airglow emission rates from such a reaction would be very large and much of the discussion of the nightglow has been concerned with finding suitable deactivation mechanisms to give the observed low intensities (Bates, 1955; Barth and Patapoff, 1962; Dalgarno, 1963; Barth, 1964). Arguments by Young and Sharpless (1962, 1964) have been presented, however, to show that laboratory derived reaction rates for deactivation and for competing activations indicate that the simple three-body reaction above is not adequate to account for the nightglow intensities. The basic excitation mechanism is still not clear.

In addition to the total emission rates the relative intensities of the various bands and the population distribution among the upper vibrational levels must be accounted for. Figure 6A shows a plot of the band intensities listed in Table II. The lines connect bands arising from a common upper vibrational level with $\underline{v}' = 7$, 6, 5, and 4 and ending in the various lower levels with $\underline{v}' = 0$, 1, 2, 3, 4, 5, or 6. In 6B are shown the band intensities listed in the compilation by Wallace (1962) which are in turn taken from the laboratory studies of Broida and Gaydon (1954) and Barth and Kaplan (1959). In 6C are the intensities calculated by Pillow (1953a, 1953b). In parts B and C the sum of the intensities of all the bands shown have been set equal to the sum of the corresponding bands in A. The calculations by Pillow assume, for convenience, a uniform distribution of molecules throughout the upper vibrational levels. In addition they assume a constant electronic transition moment which is almost certainly not the case (c.f. Nicholls, 1955; Broida and Gaydon, 1954). There is surprisingly good agreement between the short wavelength band intensity [illegible] observed in the

laboratory[B], where source pressures are high (2-4 torr), and those in the night sky[A], where source pressures are low (10^{-13} torr).

The distribution of vibrational levels inferred from a comparison of our data with Pillow's calculations indicate a decreasing population of the higher vibrational states. This is in distinction to the distribution inferred in the same manner from Chamberlain's (1955) estimates of intensities at the longer wavelengths, which show an increasing population of the higher vibrational states. The altitudes at which our spectra were taken would seem to preclude any absorption so the discrepancy must be sought in the calculational model or in the intensity estimates.

The study of the night airglow has progressed considerably in the last ten years but the most fundamental questions remain unanswered. What are the exact excitation mechanisms of the various emissions which will explain the intensity, the altitude, the geographical and the temporal distributions? Although the three-body reaction mentioned above is the most likely excitation mechanism of the ultraviolet nightglow there are still many questions which must be answered before it can be accepted.

ACKNOWLEDGEMENTS:

I wish to thank Lawrence Dunkelman for his long and continuing advice and encouragement for this project; Theodore Stecher, James E. Kupperian, Jr., and Don Heath for their suggestions concerning the data handling; and William Russell and Charles Laverty of the GSFC Sounding Rocket Branch for their development of the attitude control system.

TABLE I

INTEGRATED AIRGLOW EMISSION RATES

Wavelength Interval (Angstroms)		Bands Included (ν',ν'')	Zenith Emission Rate (Rayleighs)
2511	2526	7,0	0.1
2555	2578	6,0	2
2578	2610	5,0	5
2610	2649	7,1 4,0	10
2649	2691	6,1	13
2691	2725	5,1	15
2725	2765	7,2 4,1	22
2765	2802	6,2	21
2802	2839	5,2 3,1	22
2839	2884	7,3 4,2	30
2884	2924	6,3	28
2924	2989	5,3 3,2 OI 7,4	46
2989	3050	4,3 2,2 6,4	39
3050	3121	3,3 5,4 7,5	39
3121	3197	4,4 6,5 2,3	40
3191	3250	3,4 5,5 1,3	32
3250	3355	7,6 4,5 2,4 6,6	55
3355	3408	3,5 5,6 1,4	29
3408	3528	7,7 X 2,5 4,6 6,7 X	51
3528	3602	3,6 1,5 5,7 7,8	35
3602	3680	X 2,6 4,7 0,5 6,8	29
3680	3803	X 3,7 1,6 5,8 7,9 X	35
3803	3857	4,8 2,7 0,6 6,9	12

TABLE II

AIRGLOW BAND INTENSITIES

Band	Wavelength (A)	Approximate Zenith Emission Rate (R)
7,0	2519	0.1
7,1	2622	9
7,2	2732	20
7,3	2850	19
7,4	2976	10
7,5	3111	3
7,6	3257	13
6,0	2554	3
6,1	2660	13
6,2	2773	21
6,3	2894	28
6,4	3025	9
5,0	2593	5
5,1	2703	15
5,2	2819	22
5,3	2945	28
5,4	3079	20
4,0	2637	<1
4,1	2750	2
4,2	2871	11
4,3	3001	31
3,3	3063	16
OI	2972	9

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CAPTIONS

Figure 1. The airglow spectrograph. The off-axis cylindrical parabola collimator and the f/0.7 Schmidt camera make a very fast system.

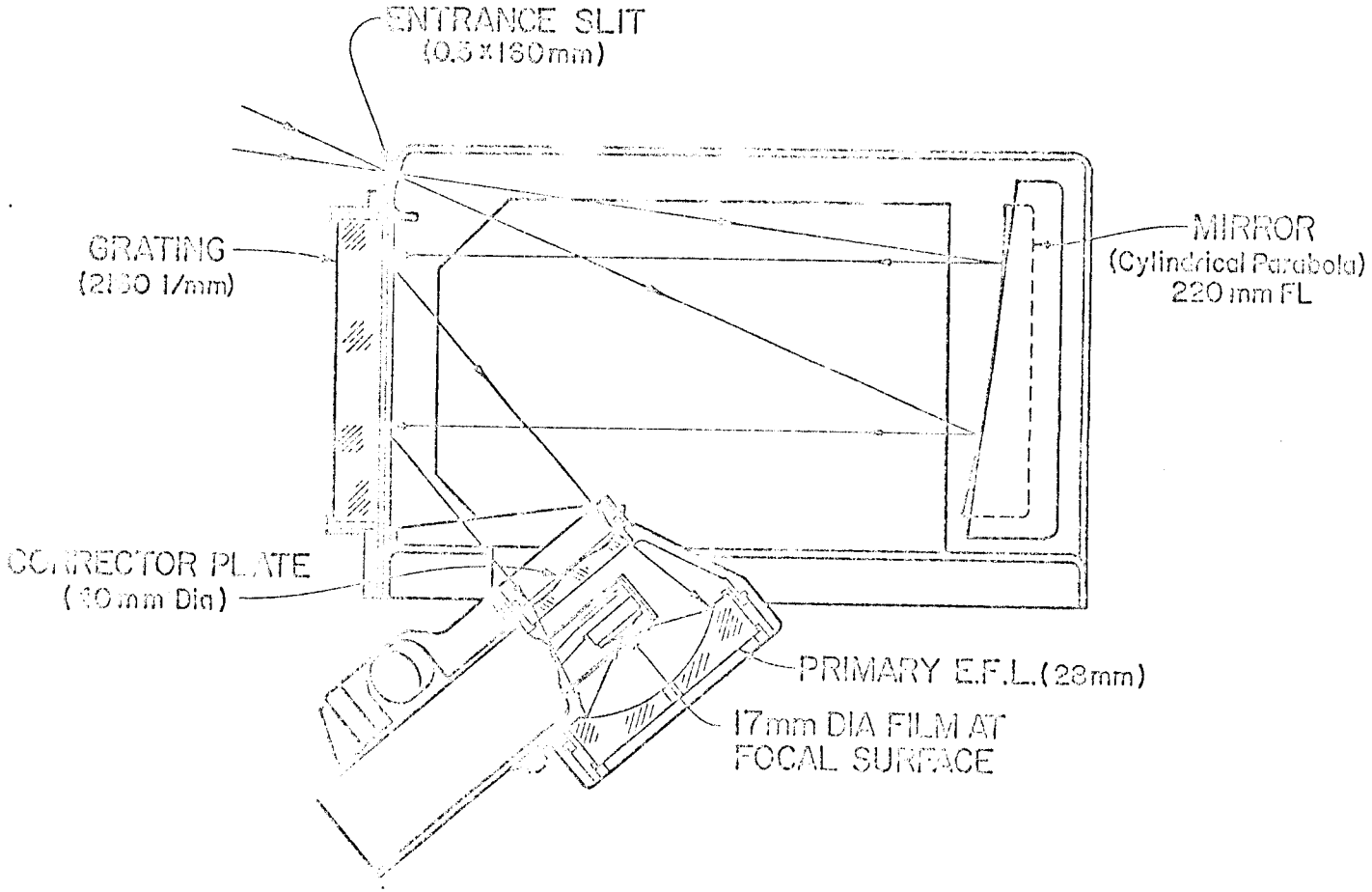
Figure 2. The Schmidt camera and film transport. Six film disks may be positioned in the image surface by a spring operated mechamism. Less than a 0.1 mm spot size is produced.

Figure 3. The airglow spectrum. An approximate wavelength scale (microns) is shown. The spectrum covers approximately 11 mm on the film.

Figure 4. A densitometer trace of the nightglow spectrum. An approximate intensity scale is shown.

Figure 5. The ultraviolet nightglow spectrum. The instrument and film response have been removed from Figure 4 and the spectrum put on a linear scale. The OI 2972A line is mixed with the Herzberg 7,4 band at 2976A. The short bars mark features not belonging to the Herzberg system.

Figure 6. A plot of the normalized intensities of the short wavelength bands as found in (A) Table II of this paper; (B) A compilation of laboratory data by Wallace (1962); and (C) a calculation by Pillow (1953b). The numbers give the vibrational number of the upper state. The curve connects transitions from a common upper state v' to various lower states v''. The lower states start at $v'' = 0$ in parts (A) and (C) but not in (B). The sum of the intensities in (B) and (C) have been set equal to the sum of the corresponding intensities in (A).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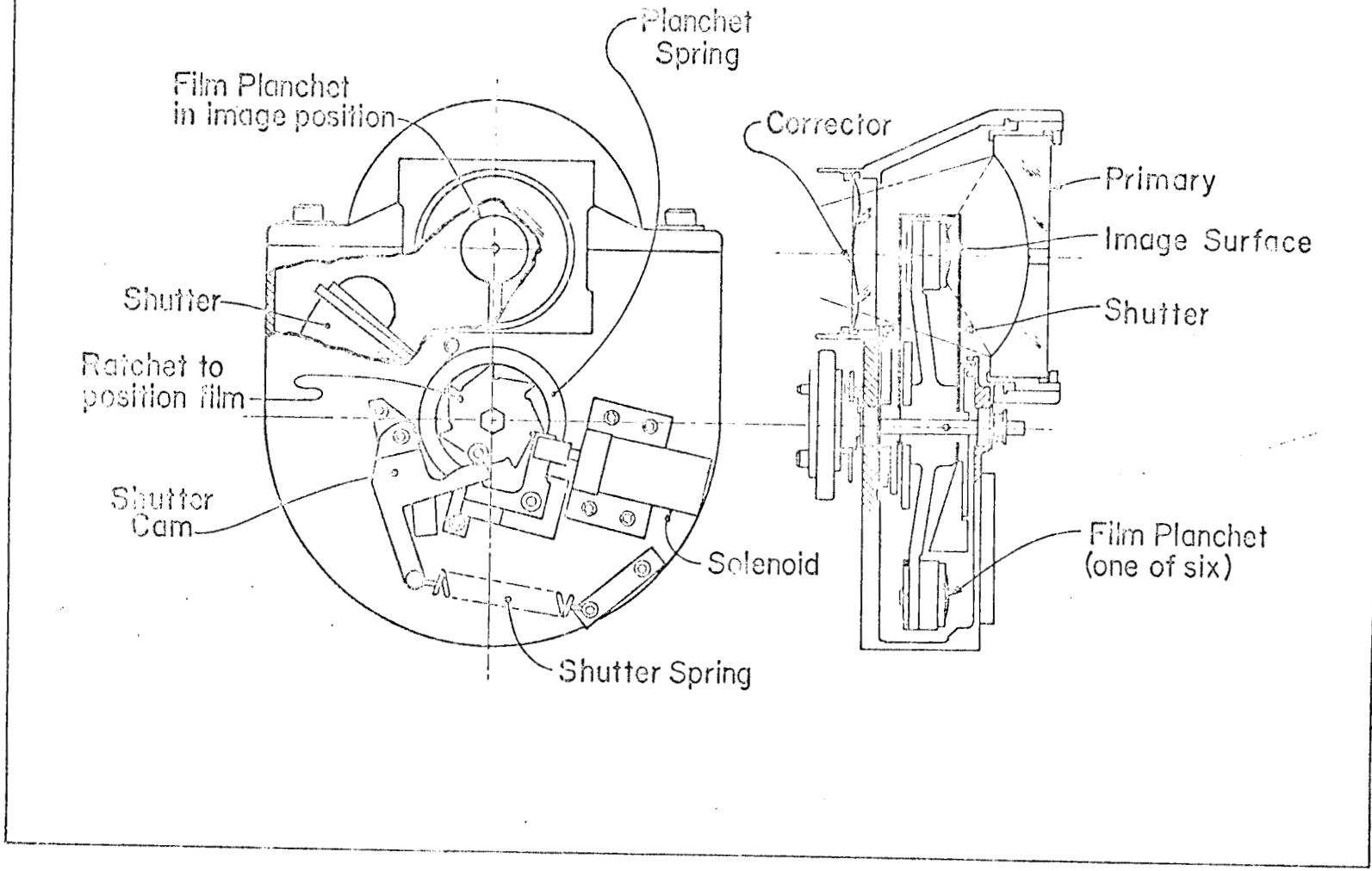
CORRECTOR PLATE
(60 mm Dia)
PRIMARY E.F.L.(28mm)
17mm DIA FILM AT
FOCAL SURFACE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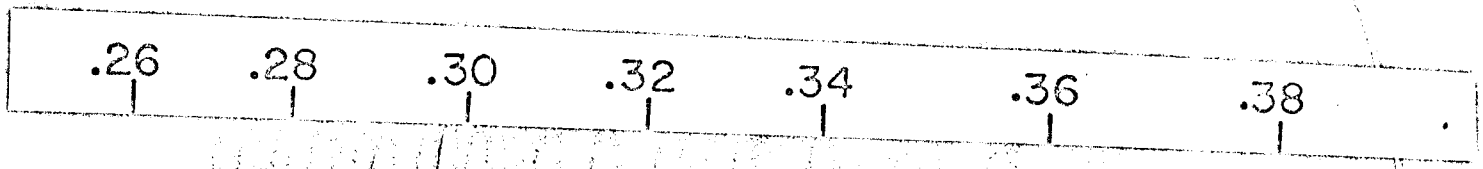
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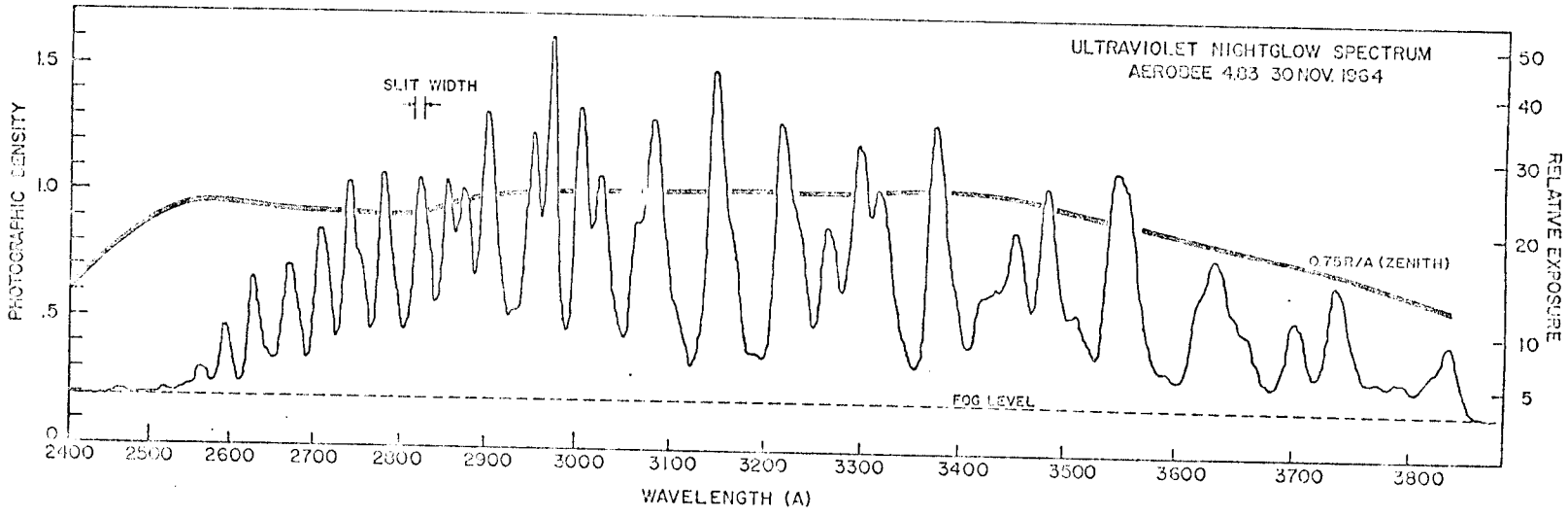
ULTRAVIOLET NIGHTGLOW SPECTRUM
AERODEE 4.83 30 NOV. 1964
SLIT WIDTH
0.75R/A (ZENITH)
FOG LEVEL
PHOTOGRAPHIC DENSITY
RELATIVE EXPOSURE
WAVELENGTH (A)
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.5
1.0
1.5
5
10
20
30
40
50
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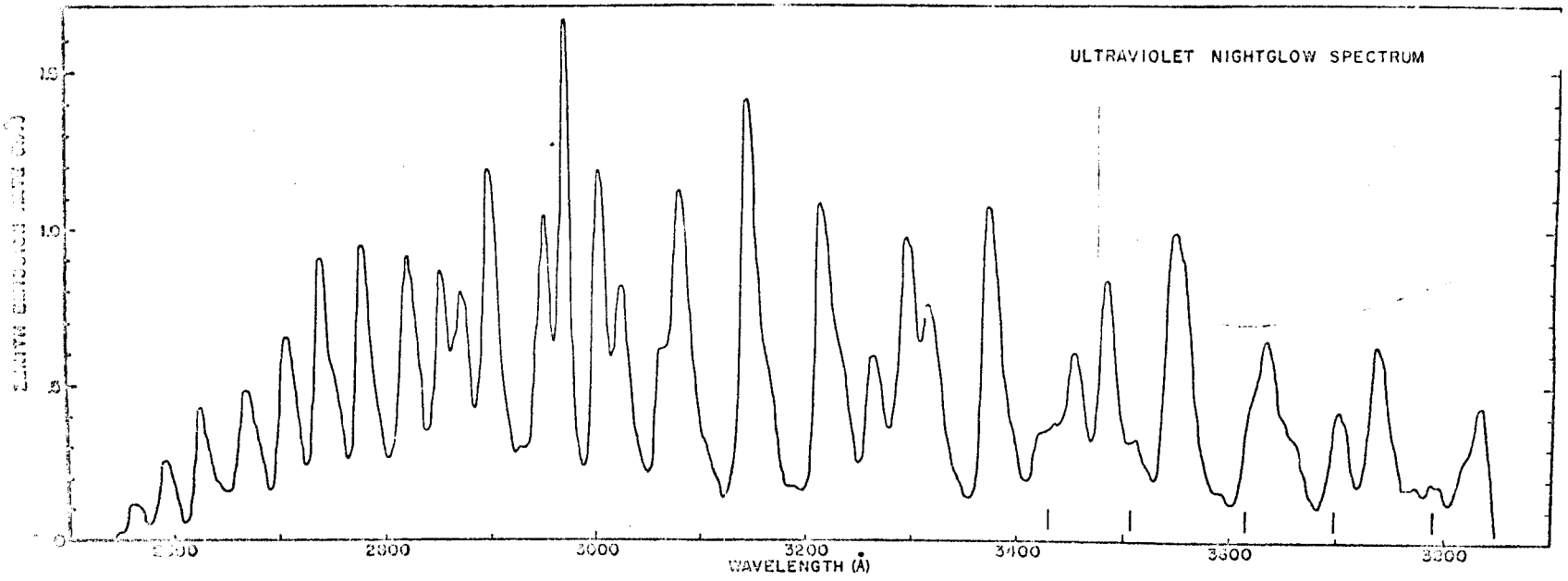
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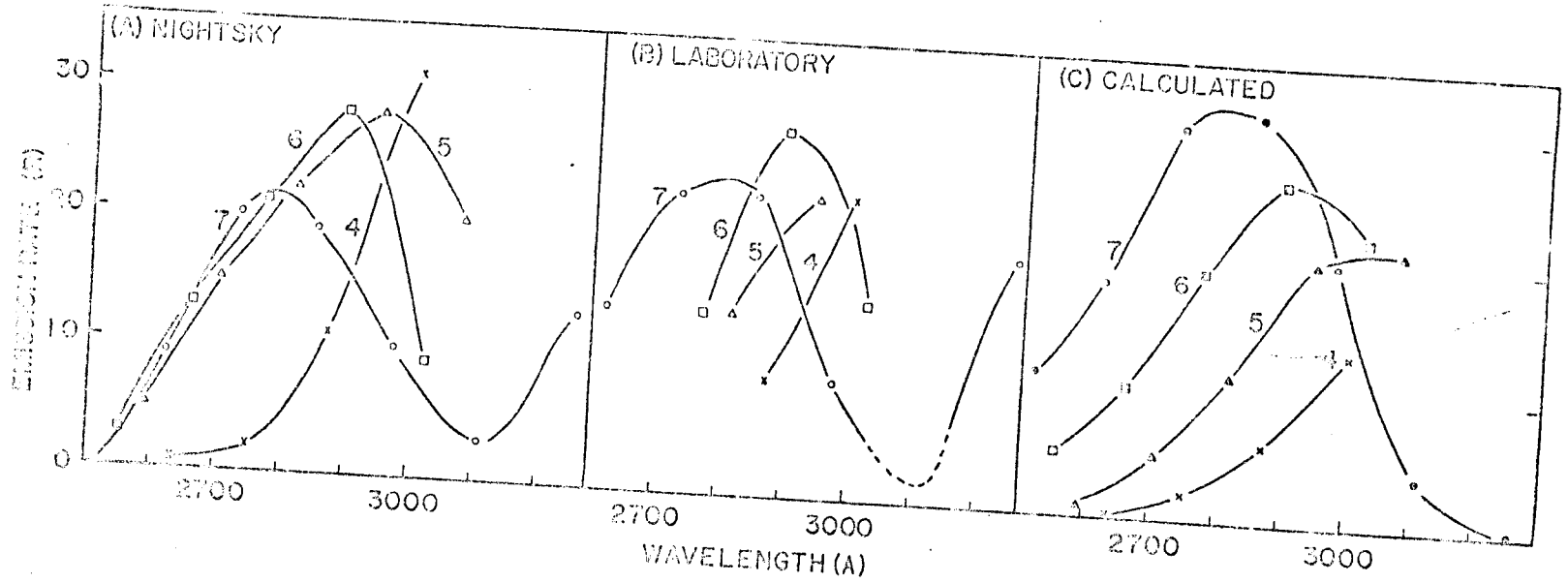
3000
3200
3400
3600
3800
WAVELENGTH (Å)


(A) NIGHT SKY
(B) LABORATORY
(C) CALCULATED
INTENSITY (R)
30
20
10
0
7
6
5
4
2700
3000
WAVELENGTH (A)