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Observations of a Searchlight Beam to an Altitude of 28 Kilometers

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Abstract

The beam of a high intensity searchlight directed over an observing station 18.4 km distant at angles of 30° and 45° to the horizontal was visible to a vertical altitude of about 20 km and was photographed to 28 km on clear nights. The intensity of the beam measured from the photographs was of the same order of magnitude as that calculated from the Rayleigh theory of molecular scattering using standard tables of stratospheric densities. At 5 km the observed intensity was greater than the theoretical intensity by a factor of about 7, the factor decreasing to about unity above 10 km, as would be accounted for by a small number of haze particles at 5 km which decreased to an imperceptible amount above 10 km.

Introduction

1. The use of a searchlight to investigate the atmosphere to considerable altitudes has often been proposed. Synge (1) suggested the concentration of several searchlight beams at a high region and the measurement with a photoelectric cell of the light scattered from the region. With a sufficient number of searchlights, it appeared that the light scattered from an altitude as high as 30 km might be detected, and that the limit of altitude obtainable would finally be set by the background illumination of the night sky and the stars. To reduce the limitation Tuve, Johnson and Wulf (2) discussed the possibility of employing a modulated beam and detecting by a photoelectric cell and amplifier tuned to the modulation frequency. From the known characteristics of large searchlights and of the amplification of photoelectric cell circuits they estimated that the light scattered from altitudes above 50 km might be measurable. The only recorded experimental observations appear to be those of Duclaux (3) who photographed from a distance of 2.4 km the vertical beam of a 5 ampere arc at the focus of a 30 cm mirror. With an F/1.5 lens and an exposure of 1 hour and 30 minutes on a clear moonless night the beam was traceable on the plate to an altitude of 3.4 km. It was of interest to carry the experiment further, and as described in the following paragraphs the beam of a high power searchlight was photographed in clear weather to an altitude of about 28 km. The measured intensity of the beam was in fair agreement with that attributable to molecular scattering, being slightly in excess as would be accounted for by a few haze particles.

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(1) Synge, Phil.Mag. 9, 1014 (1930).

(2) Tuve, Johnson and Wulf, Terr.Mag. and Atmos.Elec. (1935)

(3) Duclaux, Jr. de Phys. et Rad. 7, 361 (1936)

Experimental Observations

2. A high intensity carbon arc searchlight was provided and operated by the United States Army Engineers. The mirror was 152 cm (60 inches) in diameter and 62 cm in focal length, the arc consumed 150 amperes at 78 volts, or 11.7 kilowatts. The angular width of the beam was 1.2°. Observations were made from a station in Virginia 18.4 km to the northwest of the searchlight; there was no disturbing artificial illumination. A camera with an F/1.8 lens and 45 x 60 mm plates was used to photograph the beam. The night of April 12, 1937, was clear with no moon; the beam was directed over the observing station at an angle of 30° to the horizontal. Four pictures were taken which are shown in Plate 1, the vertical altitudes of the beam and the times of exposure, derived from the star tracks, being marked along side of each picture. Pictures B, C and D were taken on Hypersensitive panchromatic plates and A on Verichrome film. The geometry of the scene and the portion of the beam on each plate is drawn in Plate 2 in which S and P were the positions of the searchlight and the observers, respectively. Up to an altitude of 1.8 km the beam was bright and unpolarized indicating scattering by haze. At this point there was a sharp step-down in intensity, seen in A Plate 1, as the beam passed out of the stratum of low lying haze. The haze was actually very slight, the atmosphere near the ground being normally, but not abnormally, clear. The increased intensity of the beam in the stratum of faint haze was entirely expected, for it is a familiar fact that the lateral scattering of a beam of light is enormously increased above that due to air molecules by what would be ordinarily termed an almost unnoticeable amount of haze. Above 1.8 km the brightness of the beam decreased slowly and uniformly along the beam until it faded to indistinguishability against the stars. It was visible to the eye to more than 30° beyond the zenith or to an altitude above 18 km. Tests with yellow and orange filters showed that for altitudes above 5 km a considerable portion of the light of the beam was in the bluepart of the spectrum. To the dark adapted eye the beam appeared of course whitish rather than bluish.

3. In Plate 1, D the beam was easily visible entirely across the plate amid the star tracks and was considerably brighter than the night sky background. The short horizontal lines at a, b and c alongside of B, C and D, Plate 1, mark the sections of the beam across which densitometer records were made. The negatives were less exposed at each end than in the central portions because the camera lens yielded its full aperture only in the central half of the negative. Therefore only the sections a, b and c in the central portion of each negative were used for intensity measurements.

4. In another experiment on May 10, 1937, the beam was pointed up at an angle of 45° to the horizontal passing through the zenith of the observing station. The night was very clear and without a moon; there was no noticeable concentration of slight haze near the ground as occurred on April 12. The beam was visible to a point slightly beyond the zenith or to an altitude of about 20 km. With the camera directed overhead to embrace the region E, Plate 2, a single photograph was taken with an exposure of 54 minutes between 9 and 10 P.M. The region E was purpose-

ly chosen to yield the photographic limit of the beam under the experimental conditions which prevailed. On the negative the beam could be followed to 28 km but not to 30 km. The negative was not suitable for reproduction for the trace of the beam was too faint. There was a general fogging due to night sky light and stars, and a longer exposure would not have given a greatly increased length of the beam. During the early part of the exposure the zodiacal light was visible in the west and an aurora in the north; these apparitions were faint, but were unusually strong for this latitude. The general night sky illumination may have been unusually strong also, although it was not perceptible to the untrained eye. It seemed probable that the altitude of 28 km was not far from the limit attainable by photography of the 11.7 kw searchlight. To reach higher altitudes a more intense beam would be necessary and a more favorable climatic location as a mountain top would be desirable.

5. The altitude 28 km was about 6 km above the height attained by the stratosphere balloon (4) Explorer II. It was probably well into the

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(4) National Geographic Society - U.S. Army Air Corps Stratosphere Flight of 1935.

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ozone region, the lower boundary of which was at about 20 km according to the observations of Explorer II.

6. The atmospheric conditions during the above observations were the clearest which occurred during the experimental program. When the atmosphere was not clear the haze affected the beam as anticipated. For example, a fair amount of haze brightened the beam very much at low altitudes by increased scattering and decreased the brightness at the higher altitudes by absorption, the decrease being due to the degradation of the beam in its passage through the haze and to the fact that the observers on the ground were looking at the beam through haze.

Observed and Theoretical Intensity of the Beam

7. It was of interest to compare the intensity of the light of the beam determined from measurements of the photographs with the intensity calculated from the scattering of the air molecules. The complete details of the two sets of calculations are given in Appendices 1 and 2, the more important steps are mentioned briefly here.

8. In order to measure the intensity of the beam from the negatives a part of each negative had previously been cut off and kept in reserve. A calibrated tungsten lamp with a blue filter served as a source of known intensity of light of spectral characteristics approximately the same as those of the scattered light of the beam. With the source at various distances a series of spots of known intensities were impressed on the reserved pieces of each negative, the intensities being so chosen that the weakest was weaker than the beam and the strongest was stronger than the beam. All the negatives and the reserved pieces were developed in the same developing bath at the same time. Densitometer records were taken across each negative at sections a, b and c, Plate 1, and also across each spot on the reserved pieces. From these, omitting tedious and obvious details, the intensities of the central portion of the beam at various altitudes were determined and are given in column (3), Table 1.

9. It may be noted in passing that the energy flux from a sheet of white paper in the light of the full moon is about 1 erg cm^{-2} sec^{-1}. This is about 10 times the intensity of the beam at an altitude of 4.8 km, shown by a, negative B, Plate 1.

10. The calculation of the intensity of the beam from the theory of molecular scattering made use of the known candle power of the beam and the spectral intensity distribution of the light of the high intensity carbon arc. The flux of energy in each wave-length was calculated at various distances from the searchlight on the assumption that absorption of the beam by the atmosphere was relatively small. The molecular densities at the various heights were taken to be those of Table 2, which were derived from Humphrey's tabulations (5). The values were changed by less

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(5) Humphreys, Physics of the Air, page 74 (1929)

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than 5 percent by the use of the actual atmospheric pressure and temperatures observed during airplane flights to 5 km on the days of the searchlight experiments. Introducing the above quantities into the Rayleight scattering formula, and integrating across the beam at the required angles, yielded the theoretical values of the intensity of the beam corresponding to those determined from the photographs. They are given in column (4), Table 1.

11. It is difficult to estimate the possible errors in the numbers of columns (3) and (4), Table 1; they, and those of column (5), may be correct within a factor of 2. With this qualification the theoretical in-

tensities of column (4) deviate in a regular manner from the observed intensities of column (3) as shown by the ratios of column (5). The ratios decrease from about 7 at 5 km to unity at 10 or 15 km. The deviations would be accounted for by the assumption of a small number of scattering particles, such as haze, which decreased with increasing altitude. About 100 particles cm^{-3} of diameter 0.1μ and albedo 1 would yield the factor 7; or, a larger number of smaller particles of less albedo. Such a haze distribution would increase the intensity of the beam in the lower levels above that due to molecular scattering without at the same time attenuating the beam appreciably in the higher levels.

12. It is concluded that for a relatively clear atmosphere in levels above 5 km the intensity of the searchlight beam was of the order of magnitude of that calculated from the theory of molecular scattering using the density of air molecules of a standard atmosphere, Table 2. At 5 km the observed intensity was greater than the theoretical intensity by a factor of 7, the factor decreasing to about unity above 10 km, indicating the presence of a small number of haze particles at 5 km which decreased to an imperceptible amount above 10 km.

13. In conclusion it is a pleasure to acknowledge the cooperation of Major William Sackville, U.S.A., in arranging for the operation of the searchlight.

Table 1

Intensity of Searchlight Beam

(1)		(2)	(3)	(4)	(5)
			Intensity of beam erg cm-2 sec-1		
Negative		Altitude	From photograph	From theory	ratio (3)/(4)
E		22 km	(0.7) x 10^{-5}	0.49 x 10^{-5}	(1)
D	c	11.0	0.54 x 10^{-3}	0.22 x 10^{-3}	2.5
	b	10.4	0.54 "	0.24 "	2.3
	a	9.8	0.54 "	0.25 "	2.2
C	c	8.7	0.93 "	0.28 "	3.3
	b	8.2	1.9 "	0.34 "	5.6
	a	7.6	2.5 "	0.39 "	6.4
B	c	6.7	3.8 "	0.59	6.4
	b	5.8	6.3 "	0.94 "	6.7
	a	4.8	9.7 "	1.34 "	7.1

Appendix 1

Photographic Determination of the Intensity of the Beam.

A ribbon filament tungsten lamp, standardized by the National Bureau of Standards, burning at a red ($\lambda 0.655\mu$) black body apparent temperature of 1719° K, served as a known source of energy. A diaphragm limited the exposed area of the filament to 0.124 cm^2. A selected blue filter of known transmission was placed in front of the lamp; the spectral energy curve of the light through the filter is given in curve 1, Plate 3. The calculated spectral energy curve of the scattered light of the searchlight beam is given in curve 4, Plate 3. The curve is limited to the wave-length region from about 3800 A to 7000 A, the lower limit being set by the transmission of the camera lens and the upper limit by the sensitivity curve of the photographic plates. Curves 1 and 4 cover approximately the same spectral region, and since the sensitivity of the photographic plate did not vary rapidly through the region, the tungsten lamp with the blue filter was considered a satisfactory source for calibration purposes. The total energy emitted in a hemisphere by the filament through the filter, given by the area under curve 1, Plate 3, was 2.58×10^3 erg sec^{-1}, and the flux at a distance r was

$$2.58 \times 10^3/2\pi r^2 \quad \text{erg cm}^{-2}\ \text{sec}^{-1} \qquad (1)$$

With the lamp at six different distances six spots were photographed on the reserved pieces of the negatives with 5 minute exposures, each spot being caused by a known intensity of light determined by (1). As already mentioned, densitometer traces of the spots were made from which the intensities of the central portions of the beam at various altitudes were determined, the values being given in column (3), Table 1.

Appendix 2

Theoretical Calculation of the Intensity of the Beam

The spectral intensity curve of the high intensity carbon arc from the measurements of Kalb (6) is shown in curve 2, Plate 3, in which the

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(6) Kalb, Elec. Eng. 56, 319 (1937)

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intensity i_λ is plotted as ordinate against the wave-length λ as abscissa. The observations extended only to 1.2μ; the curve was extrapolated to longer wave-lengths as indicated by the dotted portion. The hump at 0.38μ is due to the cyanogen band emission. Curve 3 is the spectral energy curve of black body radiation at 5600° K. The agreement between curves 2 and 3 throughout the visible spectrum from 0.4 to 0.7μ shows that the spectral characteristics of the visible light of the high intensity carbon arc were similar to those of a black body at 5600° K.

At 1,000 yards from the searchlight the luminous intensity was 28, 24, 14 and 4 lumens ft.$^{-2}$ at 0°, 0.2°, 0.4° and 0.6°, respectively, from the center of the beam. Therefore the average brightness of the beam across 1.2° was 18 lumens ft.$^{-2}$, or 1.93×10^{-2} lumens cm.$^{-2}$. The intensity of the searchlight did not fluctuate more than 5 percent during an hour's operation. Multiplying 1.93×10^{-2} by 1.5×10^{-3} to convert to luminous watts (7) by 1/0.132 to convert to mechanical watts and by

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(7) Hyde, Forsythe and Cady, Phys.Rev.13, 45 (1919)

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10^7 to convert to ergs, yielded 2.28×10^3 erg cm^{-2} sec^{-1}. From this the energy flux i of the beam at any distance from the searchlight was calculated from the inverse square law. The number 0.132 is the radiant luminous efficiency of black body radiation at 5600° K (8).

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(8) Coblentz and Emerson, Bul.Bur.Stand. 14, 255 (1917)

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Further,

$$i = \int_0^\infty i_\lambda \, d\lambda \,, \qquad (2)$$

and is given by the area under curve 2, Plate 3.

If a beam of unpolarized light of intensity i_λ erg cm^{-2} sec^{-1} and wave-length λ passes through a gas of refractive index μ and n molecules cm^{-3}, the intensity $i_{s\lambda}$ of the light scattered at an angle θ to the beam is

$$i_{s\lambda} = i_\lambda \frac{2\pi^2 (\mu - 1)^2}{n\lambda^4} (1 + \cos^2 \theta) \qquad (3)$$

(3) is derived from the Rayleigh (9) theory of scattering by particles small with respect to λ. The $i_{s\lambda}$, λ curve for the radiation of curve 2 scattered by air is plotted in curve 4, Plate 3. Integrating (3) over

(9) Rayleigh, Phil.Mag. 51, 107, 274 (1871); 47,375 (1899)

a sphere gives, as it should, the Rayleigh expression for β the attenuation due to scattering,

$$\beta = 32 \pi^3 (\mu-1)^2/3\, n\, \lambda^4$$

Now

$$\mu-1 = \alpha\, n, \qquad (4)$$

where α is a function of λ. α has been measured (10) for air throughout the wave-length region from 2000 to 10,000 A. Substituting (4) into

(10) Meggers and Peters, Bul. Bur. Stand. 14, 731 (1918)

(3) yields

$$i_{s\lambda} = i_\lambda\, 2\, \pi^2\, n\, \alpha\, (1+\cos^2\theta)/\lambda^4 \qquad (5)$$

(5) expresses the scattered intensity explicitly in terms of the moledular density n.

The total scattered light i_s from unit volume of the beam in wave-lengths from 3800 to 7000 A is

$$i_s = \int_{3800}^{7000} i_{s\lambda}\, d\lambda \qquad (6)$$

and is given by the area under curve 4, Plate 3.

The intensity of the beam i_b is the total scattered light from the beam in a direction θ, and is the integral of i_s across the beam at $\angle\, \theta$. Since the beam diverges only slightly we have to a close approximation

$$i_b = i_s\, f/\sin\theta, \qquad (7)$$

where f is the diameter of the beam at the point in question.

By means of equations (2) to (7) and n from Table 2, the values of i_b were calculated for a, b and c of pictures B, C and D, Plate 1, and for an altitude of 22 km from picture E. They are tabulated in column (4), Table 1.

Appendix 3

Atmospheric Molecular Density

To determine the molecular density n we make use of the average values of the atmospheric density d and temperature to 40 km tabulated by Humphreys (5); they are given in Table 2, d being in grams cm-3. The values were based on European observations of the temperatures and pressures to 20 km and extrapolation above on the assumptions that the temperature was -55° C from 20 to 40 km and that the atmospheric composition was the same as at sea level. The values were, within 2 percent, the same as those adapted to 24 km as the "U.S. standard atmosphere." (11)

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(11) Nat.Adv.Com.Aer.Technical Report No. 538

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The mass of the average air molecule is 4.95×10^{-23} grams, and

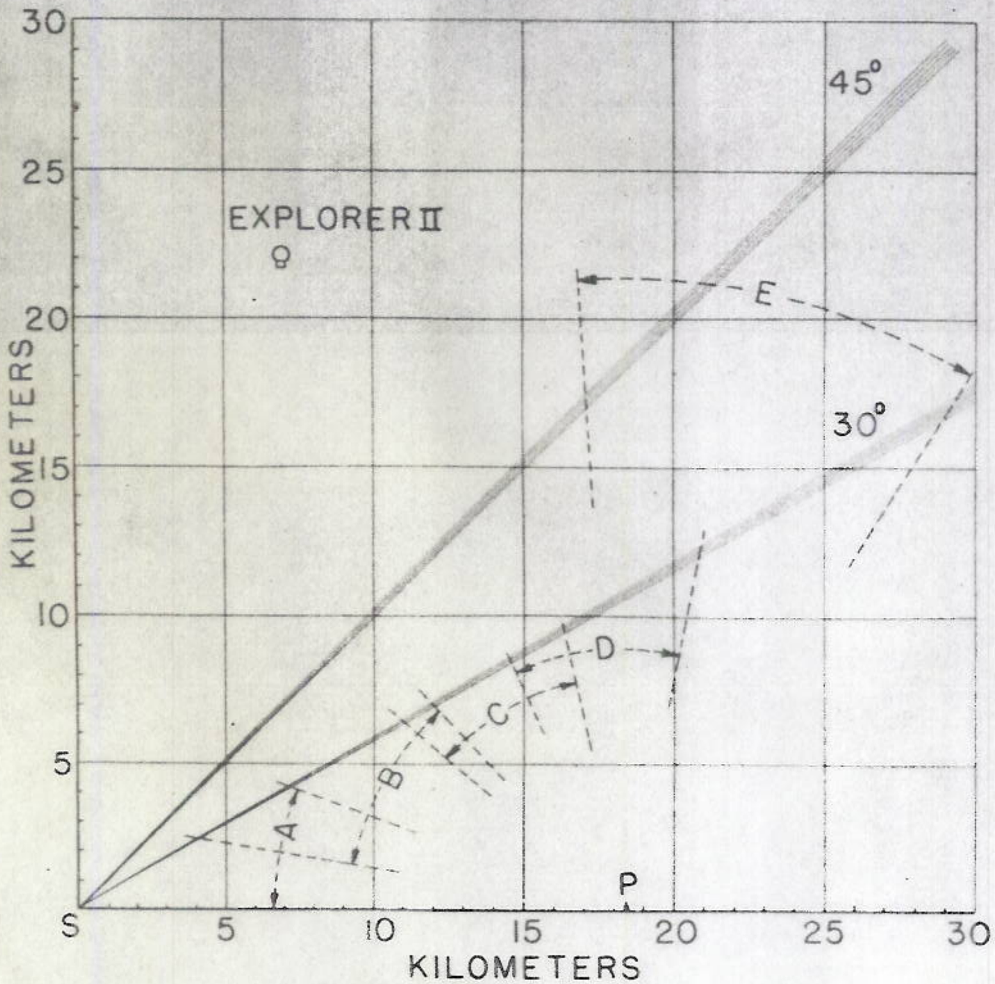
$$n = d/4.95 \times 10^{-23} \qquad (8)$$

The values of n from (8) are in the last column of Table 2.

Table 2

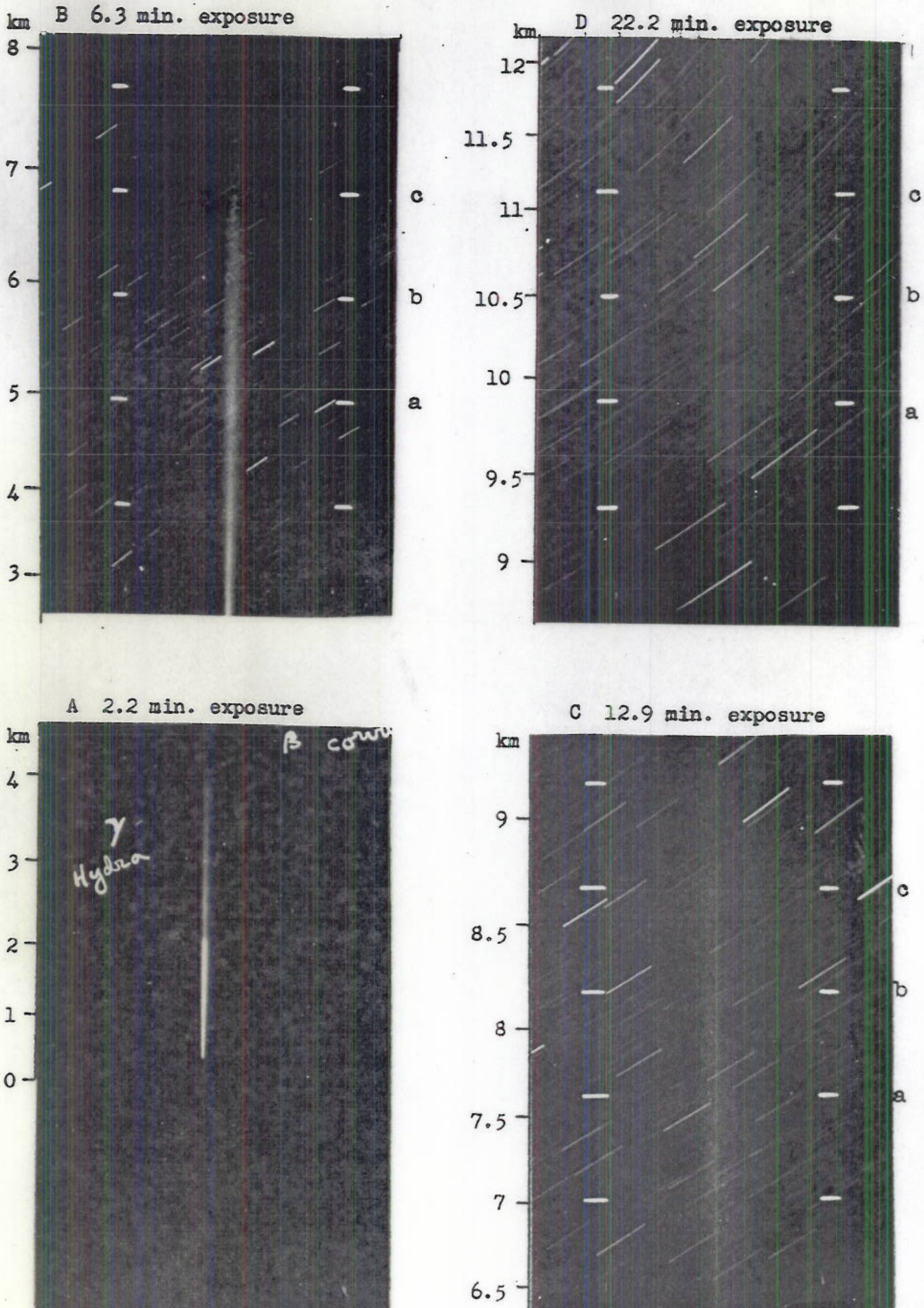
Average Temperature and Density of the Atmosphere

Altitude	Temp.	Density d	n	Altitude	Temp.	Density d	n
0 km	1.72°C	1256×10^{-6}	254×10^{17}	20 km	-55°C	89.7×10^{-6}	18.1×10^{17}
2	-4.16	1010	204	22	-55	65.8	13.3
4	-15.3	817	165	24	-55	48.2	9.72
6	-29.3	660	134	26	-55	35.3	7.15
8	-43.6	529	106	28	-55	25.9	5.22
10	-54.2	414	83.7	30	-55	19.0	3.84
12	-55	311	63.0	32	-55	13.9	2.82
14	-55	228	46.2	34	-55	10.2	2.06
16	-55	167	33.8	36	-55	7.54	1.52
18	-55	121	24.4	38	-55	5.53	1.12

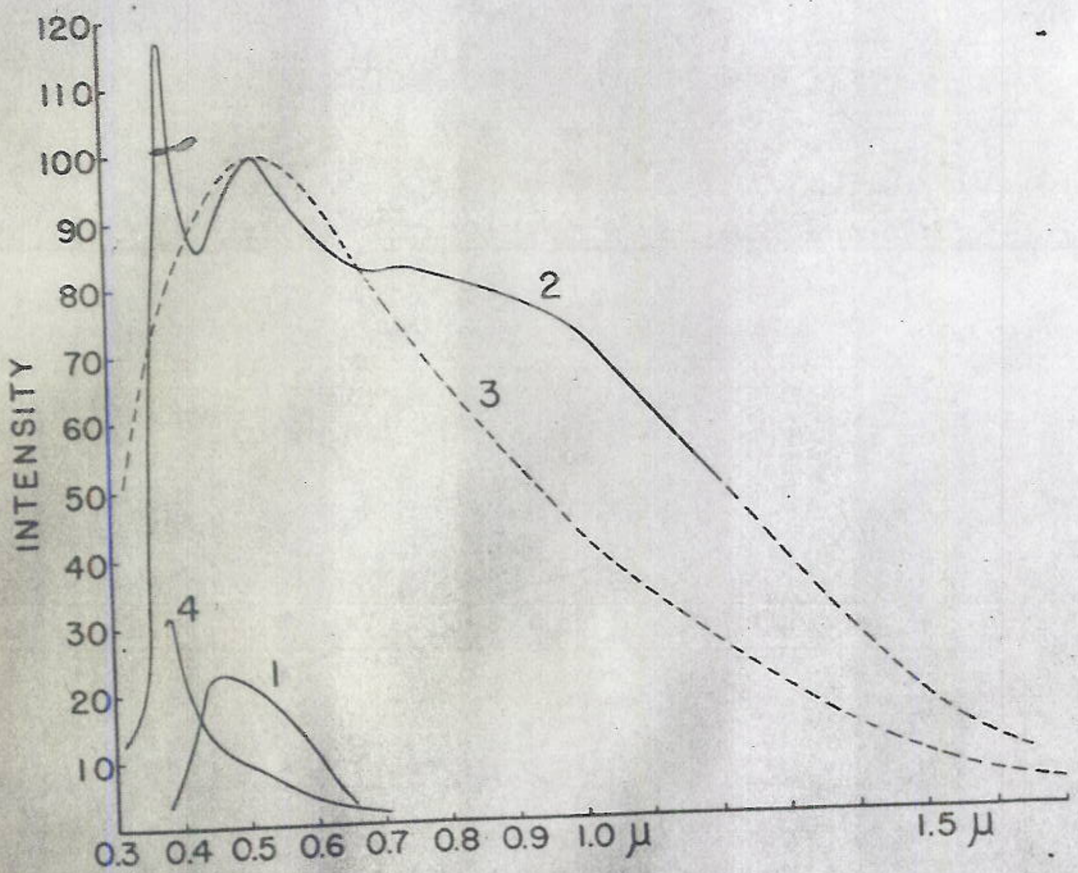


GEOMETRY OF SEARCHLIGHT SCENE

PLATE 2



Photographs of Searchlight Beam Plate 1



SPECTRAL ENERGY CURVES

PLATE 3