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MEASUREMENTS OF ULTRAVIOLET SOLAR- AND SKY-RADIATION INTENSITIES IN HIGH LATITUDES

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ABSTRACT

Data are given on the intensity of the biologically effective ultraviolet radiation, of wavelengths 3200 A and shorter, from the sun and the entire sky, incident on a horizontal plane, under various meteorological conditions, in high latitudes. These data were secured by means of a photoelectric cell and automatic recording apparatus, whereby a continuous record of ultraviolet intensities, in absolute value, was obtained during the voyage of the Louise A. Boyd Arctic Expedition, up the west coast of Greenland to Etah (lat. 78.3° N) and down the coast of Baffin Land and Labrador.

The outstanding results of this survey are, that, for the same solar heights, in the highest latitudes visited (78° N) the ultraviolet intensities appear to be somewhat higher than in latitude 62° N, but somewhat lower than in latitude 39° N (Washington), in agreement with expectation, taking into consideration the distribution of ozone in the stratosphere with latitude and the season. In the highest latitudes, at the noon hour, on the clearest days, in mid-summer, the intensity of the ultraviolet solar and sky radiation ranged from 30 to 40 $\mu W/cm^2$, which is a significant value biologically, of especial interest to the medical profession in connection with the question of the incidence of rickets.

CONTENTS

I. INTRODUCTION

Although the principal purpose of the Louise A. Boyd Arctic Expedition [1] [1] was to secure data on radio-wave propagation, the voyage presented an excellent opportunity for the Radiometry Section of the Bureau to extend its survey of intensities of ultraviolet solar radiation incident in different localities [7, 8, 9].

By installing simple automatic measuring and recording apparatus [2, 3], for the first time a continuous record was obtained, in absolute value, of the intensity of the biologically effective ultraviolet radiation from the sun and from the entire sky incident on a horizontal plane, under various meteorological conditions, in the polar regions. The information thus obtained is novel and is of considerable biological interest, particularly to the medical profession.[2]

[1] Numbers in brackets indicate the literature references and notes at the end of this paper.

[2] Acknowledgment is made to the Council on Physical Therapy of the American Medical Association for two grants in aid to develop this type of ultraviolet meter [2] for use in heliotherapy. In an unforeseen manner the first practical application of these instruments has been to the securing of quantitative data on ultraviolet intensities in the polar regions.

The voyage was up the west coast of Greenland to Etah (lat. 78.3° N) and down the coast of Baffin Land and Labrador. The herein-described ultraviolet measurements were secured by F. R. Gracely, member of the expedition from the Radio Section of this Bureau.

In connection with the present survey of ultraviolet intensities in the polar regions, practically only three previous sets of measurements are available for comparison; and these are not on a strictly quantitative basis.

The first set of measurements, by Dannmeyer [4], were made in the summer of 1927, at a sea-level station in Iceland (lat. 64° to 66° N), using a *Cd*-photoelectric cell. No description was given of the photoelectric cell; but presumably it was of the type then in common use, consisting of a spherical bulb of Uviol (or quartz) glass having one-half of the interior covered with a thin layer of *Cd*-alloy, which is photosensitive to wavelengths shorter than 3200 A.

In the absence of a primary standard, in absolute units, Dannmeyer compared his photoelectric cell with the *Cd*-photocell used earlier by Dorno (and designated the Dorno Standard) on the "volt-second" basis, as measured with an electrometer.

The outstanding results of Dannmeyer's measurements, of interest in the present work, are: (a) for the same solar height (say 30°; air mass, $m=2$) the total intensity of the ultraviolet radiation from the sun and the sky was not markedly higher than that of similar sea-level stations in lower latitudes (except Hamburg, lat. 55.5° N; air probably polluted by smoke); and (b) when the solar altitude was low (30° down to 10°; $m=2$ to 6), the intensity of the ultraviolet radiation from the sun, incident on a horizontal plane, was only one-third to one-seventh of that from the whole sky.

The biological significance of the large amount of ultraviolet sky radiation is discussed by Dannmeyer, who comments on the fact that in Iceland, in the early spring, long before the sun can shine into the deep fjords, the faces of the inhabitants take on a ruddy color that develops into a dark-brown tan in midsummer, when exposed to both sun and sky radiation.

The second set of ultraviolet solar radiation measurements of interest in the present work were made by Kestner [6] in 1926 and in 1927 on the Lofoten islands, latitude 67.3° N. Weather conditions were never perfect; but considering days of the same degree of haziness (as it appeared to the eye) in the suburbs of Hamburg, and in higher latitudes, from his measurements he concluded that, for the same solar heights, the intensity of ultraviolet radiation north of the Arctic circle is greater than in mid-Europe. Referring to figure 1, which will be more fully described on a subsequent page, if the amount of ozone is less in latitude 70° N than in latitude 55° to 60° N, as indicated in the two lower curves, then, aside from differences in atmospheric pollution by dust and smoke, the intensity of ultraviolet radiation should be greater in the higher latitude, as reported by Kestner [6].

The third set of ultraviolet measurements of interest in the present work were made by Götz [5] in the summer of 1929, at Kingsbay, Spitzbergen (lat. 78.9°), in connection with the determination of the amount of ozone in the stratosphere.

For this purpose he measured the relative intensities of certain ultraviolet wavelengths as determined from the densities of spectrograms obtained at various solar heights. No measurements were made on the total intensity of ultraviolet solar and sky radiation incident on a horizontal plane.

In connection with the present work, the chief interest in Götz's measurements is his summary of data on the variation of ozone in the stratosphere with latitude and time of the year. This is illustrated in figure 1, which is a reproduction of Götz's figure 6 [5] showing the variation in the total amount of ozone with geographic latitude and the season. The scale of ordinates is in centimeters of ozone, reduced to normal temperature and pressure.

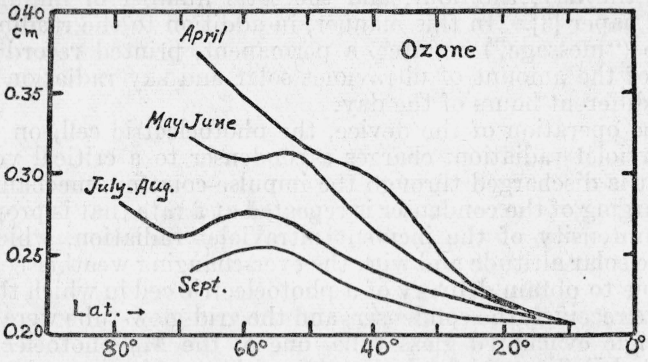

FIGURE 1.—*Curves showing the variation of ozone in the stratosphere with latitude and season (Dobson, Götz).*

Since the amount of ultraviolet solar and sky radiation incident upon the earth's surface depends upon the amount of ozone in the stratosphere, and since, as above noted, this amount varies with the geographic latitude and the season, the data on ultraviolet solar and sky intensities obtained during the present cruise are too meager for extensive correlation with latitude and season; but they are useful in showing what was available to the crew, during this expedition, and in demonstrating a simple method of obtaining such measurements in future ocean voyages.

In view of the fact that Götz [5, p. 148] seemed to doubt the accuracy of Dannmeyer's measurements showing a relatively large amount of ultraviolet radiation incident from the whole sky, at a sea-level station in Iceland, it is relevant to note (from unpublished observations made by W. W. C. and R. S.) that, with a low sun (height 30° down to 15°; approximate air masses $m=2$ to 4), the intensity of the ultraviolet radiation from the whole sky, incident upon a horizontal surface, even during the clearest days, at a sea-level station (Washington) is 3 to 15 times that of direct sunlight, in agreement with the measurements made by Dannmeyer, in Iceland.

II. INSTRUMENTS AND METHODS

The apparatus used in measuring the intensity of ultraviolet solar and sky radiation incident on a horizontal plane was composed of three parts: (a) an electronic integrating device consisting of an *Mg*-phototube, condenser, and grid-glow-tube [10] enclosed in an evacuated glass chamber which was mounted in a metal box that was attached to the top of the mainmast of the boat; (b) a metal box, below deck, containing the relay, rectifier tubes, and an impulse counter ("message counter"; see fig. 4 of reference [2]) made by R. J. Cashman; and (c) an automatic impulse recorder (modified commercial traffic recorder) which registered the impulses received from the photoelectric integrator and, at the expiration of every hour, printed the day, the hour, and the total number of impulses on a strip of paper [3]. In this manner, in addition to the reading on the impulse ("message") counter, a permanent, printed record was obtained of the amount of ultraviolet solar and sky radiation incident during different hours of the day.

In the operation of the device, the photoelectric cell, on exposure to ultraviolet radiation, charges a condenser to a critical voltage at which it is discharged through the impulse-counting mechanism; and this charging of the condenser is repeated at a rate that is proportional to the intensity of the incident ultraviolet radiation, which varies with the solar altitude and with the ever-changing weather conditions.

Unable to obtain delivery of a photoelectric cell in which the photosensitive receiver, the condenser, and the grid-glow-tube were enclosed in a single evacuated glass tube, one of the *Mg*–photoelectric cells illustrated in figure 3 of reference [2], with a condenser and grid-glow-tube, was enclosed in an evacuated glass tube and mounted in a metal box, illustrated in figure 2. Unfortunately the manufacturer placed an opaque ring around the inner tube, at such a height that it shadowed the receiver for solar heights less than about 15°. Hence, although at these low elevations the sun contributed but little relative to the ultraviolet incident from the whole sky, no attempt was made to work out the data obtained at low elevations of the sun.

Moreover, to prevent shadowing by the ship's sails, it was necessary to mount the photoelectric cell (fig. 2) in a metal box that was attached to the top of the mainmast, at a height of about 60 ft above the deck. Consequently the swaying of the mast prevented a continuous exposure of the photoelectric receiver in a horizontal position. Hence, only when the ship was in quiet water can the herein-recorded ultraviolet intensities be considered close to the true values for incidence on a horizontal surface. The records show that from August 10 to September 1 the voyage was through waters quieted by the presence of ice. When in port at Etah (August 15 to 19) and in Frobisher Bay (September 21 to 22), the water was quiet. However, since the ultraviolet radiation from the sky was no doubt four to five times [4] that of the sun, the variation in incidence by swaying of the photoelectric cell probably has not greatly affected the intensity measurements. This conclusion seems to be substantiated by the close agreement of the measurements obtained on the clearest days during the cruise with similar measurements made in Washington, taking into consideration solar height and the seasonal amount of ozone in the stratosphere. In fact, the daily totals of the impulses recorded in August were closely the same as observed on the clearest days in December 1941, in Washington, when the solar heights were closely the same as obtained during the voyage in the highest latitudes.

The calibration of a meter of this type (*Mg–3*, which includes a condenser and an electron-discharge tube [2]) to obtain intensities of biologically effective ultraviolet radiation of wavelengths 3200 A and shorter in absolute units is a relatively simple process.

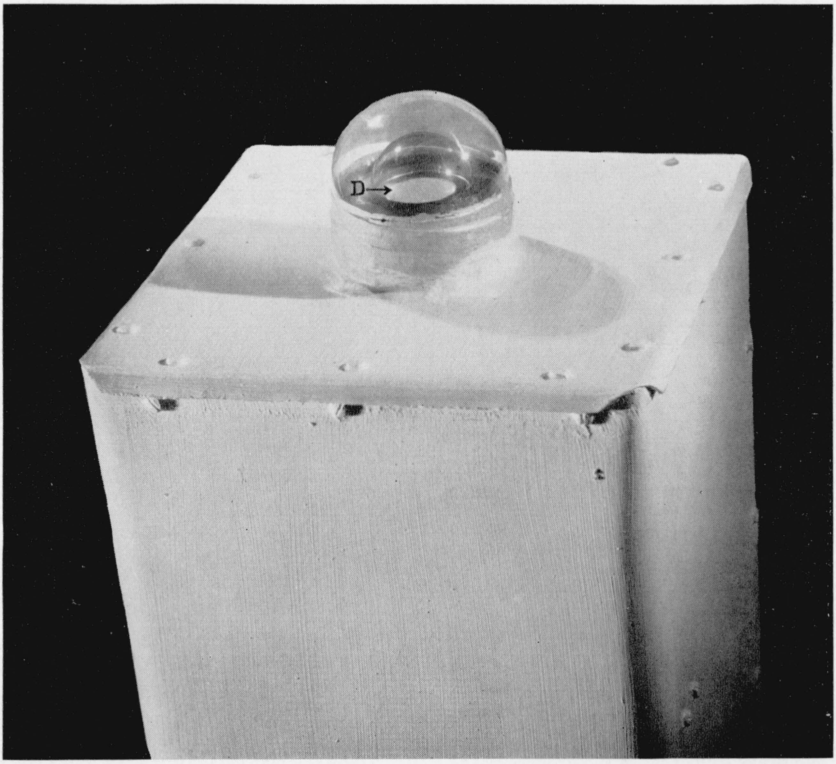

Figure 2.—*Photoelectric cell enclosed in a metal box that was attached to the top of the mainmast of the boat.*

The photosensitive, flat-disk receiver, *D*, measures the ultraviolet solar and sky radiation incident on a horizontal plane. The bright spots are unavoidable reflections of the light sources used in making the photograph.

The procedure consists in exposing the uncalibrated meter and the primary standard (*Mg 41–1*), side by side, to the sun and to the whole sky, and noting the relative number of impulses registered in a given time. Such a comparison was made before the voyage; and a more thorough comparison was made (by W. W. C.) in November and December, after the return, when the noon-hour solar heights were comparable with those that obtained at the highest latitudes (Etah; 78.3°). The comparison was made under various cloudless, cloudy, overcast, smoky, and hazy sky conditions; but no systematic difference in the ratios was observed. As shown in curve *A* of figure 3, the ratio of impulses (*Mg 41–1: Mg–3*) was uniform for air masses less

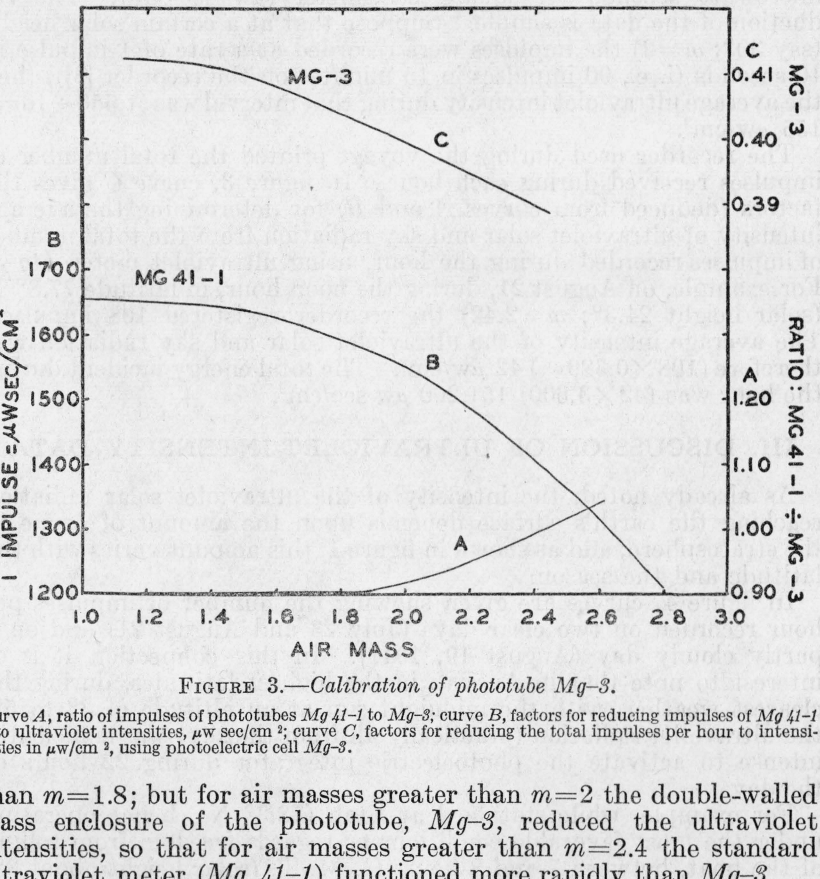

FIGURE 3.—*Calibration of phototube Mg–3.*

Curve *A*, ratio of impulses of phototubes *Mg 41–1* to *Mg–3;* curve *B*, factors for reducing impulses of *Mg 41–1* to ultraviolet intensities, μw sec/cm ²; curve *C*, factors for reducing the total impulses per hour to intensities in μw/cm ², using photoelectric cell *Mg–3*.

than m=1.8; but for air masses greater than m=2 the double-walled glass enclosure of the phototube, *Mg–3*, reduced the ultraviolet intensities, so that for air masses greater than m=2.4 the standard ultraviolet meter (*Mg 41–1*) functioned more rapidly than *Mg–3*.

The primary standard (*Mg 41–1*) is being standardized by two of the writers (W. W. C and R. S.) to measure intensities of ultraviolet solar and sky radiation of wavelengths 3200A and shorter, in absolute value, on a horizontal plane, using two methods: (a) by calibration against a standard of ultraviolet radiation [14]; and (b) by calibration against an ultraviolet-intensity meter [2, 13] that measures radiation incident normal on the photoelectric receiver. The latter was calibrated against a standard of ultraviolet radiation [14], and gave ultraviolet solar-radiation intensities (of wavelengths shorter than

3132A) in close agreement with measurements made with a balanced thermopile [11, 12, 15] which was calibrated, in absolute value, against a standard of thermal radiation. This ultraviolet-intensity meter has been in use, during the past 7 years, in measuring ultraviolet solar intensities. Although the calibration of this primary standard is incomplete, the degree of accuracy attained appears to be sufficient for evaluating the ultraviolet solar and sky intensities reported in the present paper.

In figure 3, curve *B* gives the factors for converting the impulses produced by the primary standard, *Mg 41-1*, to ultraviolet intensities (sun+sky) of wavelengths 3200A and shorter. The ordinates are in microwatt seconds per square centimeter (μw sec/cm^2). The reduction of the data is simple. Suppose that at a certain solar height (say 30°; m=2) the impulses were recorded at a rate of 1 impulse in 10 seconds (i. e., 90 impulses in 15 minutes on the recorder [3]), then the average ultraviolet intensity during that interval was (1,550÷10=) 155 μw/cm^2.

The recorder used during the voyage printed the total number of impulses received during each hour. In figure 3, curve *C* gives the factors (deduced from curves *A* and *B*) for determining the average intensity of ultraviolet solar and sky radiation from the total number of impulses recorded during the hour, using ultraviolet meter *Mg-3*. For example, on August 21, during the noon hour, in latitude 77.8° N (solar height 24.3°; m=2.42) the recorder registered 108 impulses. The average intensity of the ultraviolet solar and sky radiation was therefore (108×0.389=) 42 μw/cm^2. The total energy incident during the hour was (42×3,600) 151,200 μw sec/cm^2.

III. DISCUSSION OF ULTRAVIOLET-INTENSITY DATA

As already noted, the intensity of the ultraviolet solar radiation reaching the earth's surface depends upon the amount of ozone in the stratosphere; and as shown in figure 1, this amount varies with the latitude and the season.

In figure 4, curves are given showing the number of impulses per hour recorded on two clear days (July 23 and August 21) and on a partly cloudy day (August 19, 1941). In this connection it is of interest to note that in August, in the highest latitudes, during the clearest weather, with the midnight sun at an altitude of 3° to 5°, the ultraviolet radiation (practically all from the sky) was sufficiently intense to activate the photoelectric integrator during 22 hours of the day.

For example, while stationed at Etah (78.3° N), hence operating under the most favorable conditions as regards freedom from rolling of the boat, between 7 and 8 hours G. M. T. (solar height about 3°; m=14) the counter registered 3 impulses, and between 8 and 9 hours (S. H.=5°; m=10) it registered 5 impulses per hour, as compared with 108 impulses per hour at the noon hour (S. H.=24.4°; m=2.41).

This relatively high ultraviolet intensity when the sun was low on the horizon is not to be considered remarkable, however, in view of the fact that in the same latitude, at Kingsbay, Spitzbergen, in August 1929, Götz [5] observed intensities of total solar radiation (normal incidence) ranging from 0.35 to 0.42 (g cal/cm^2)/min at midnight (solar height, S.H.=3° to 4°) to 1.15 (g cal/cm^2)/min. at noon

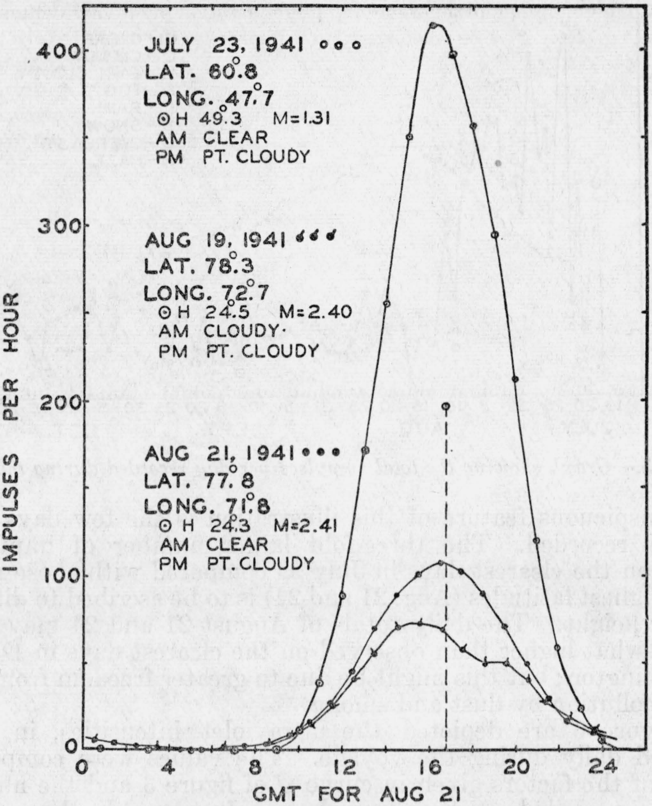

FIGURE 4.—*Graphs showing the impulses per hour received on several of the clearest days of the voyage in high latitudes.*

(S. H.=25°). He comments on the fact that the transparency of the atmosphere for total solar radiation at Kingsbay is but slightly higher than for similar solar heights (air masses traversed) in continental Europe.

In this connection it is relevant to cite unpublished records [3], repeatedly obtained in Washington, D. C., showing sufficient ultraviolet sky radiation to produce one impulse 15 minutes after sunset.

As noted above, the 108 impulses observed on the clearest day in high latitudes (August 21; lat. 77.8°; S. H. 24.4°; m=2.41) represent an average noon-hour intensity of 42 μw/cm^2. For similar solar heights in Washington the following ultraviolet solar and sky intensities were recorded [3]: October 8=46; November 17=52; December 6=44; and December 19=42 μw/cm^2. The average ratio of sky to sun radiation was 4.5 for m=2.4.

To simplify the exposition of the data on the integrated ultraviolet intensities as measured by the impulses recorded, in figure 5 are depicted the total number of impulses recorded daily (with only three interruptions indicated by broken lines) throughout the voyage in high latitudes, which are also indicated in this illustration.

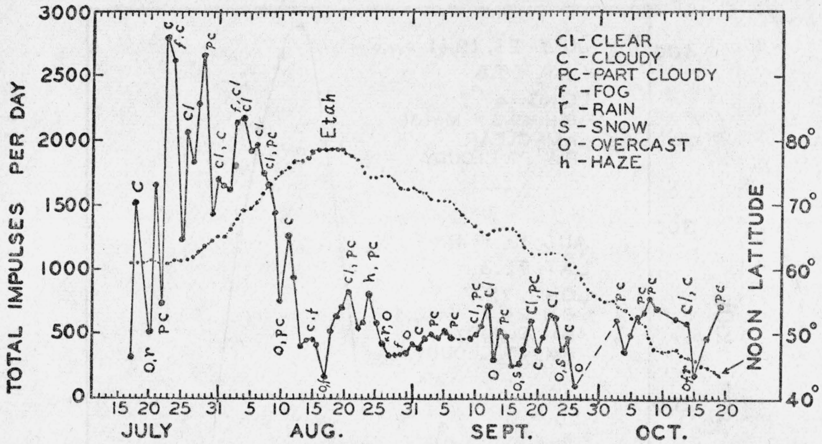

FIGURE 5.—*Graph showing the total impulses per day recorded during the voyage.*

A conspicuous feature of this illustration is the few days of clear weather recorded. The three-fold larger number of impulses recorded on the clearest days in July as compared with those recorded in the highest latitudes (Aug. 21 and 24) is to be ascribed to differences in solar height. The daily totals of August 21 and 24 may perhaps be somewhat higher than observed on the clearest days in December in Washington; but this might be due to greater freedom from atmospheric pollution by dust and smoke.

In figure 6 are depicted the ultraviolet intensities, in $\mu w/cm^2$, observed daily during the voyage. The values were computed by means of the factors given in curve *C* of figure 3 and the number of impulses recorded at the noon hour. In general, the noon hour intensities are indicative of the total number of impulses (and, hence, of the total amount of ultraviolet solar and sky radiation) received per day. Because of the above-mentioned shortcomings of this ultraviolet meter for low solar altitudes, no attempt is made to reduce the daily total impulses to total microwatt hours. Obviously, using the average intensity and the number of impulses recorded each hour, it would be a simple matter to deduce the total daily amount of ultraviolet received.

From figure 6 it may be noted that on numerous days during the voyage in August and September the intensity of the ultraviolet solar and sky radiation ranged from 30 to 40 $\mu w/cm^2$, which is a significant value biologically [12]. For example, if the erythematogenic efficiency of ultraviolet solar radiation in high latitudes is one-half that of Washington sunlight, then an exposure of 1.5 to 2 hours would produce an erythema.

In figure 7 is illustrated the variation in intensity of ultraviolet solar and sky radiation on three of the clearest days—namely, July 23, August 21, and September 22, 1941. The most conspicuous feature in this illustration is the much higher intensities in the highest latitudes (air mass $m=2.4$ to 2.8). Part of this difference may be ascribed to the seasonal change in ozone in the stratosphere, which is very marked in latitude 61° to 62° N (fig. 1), where the observations

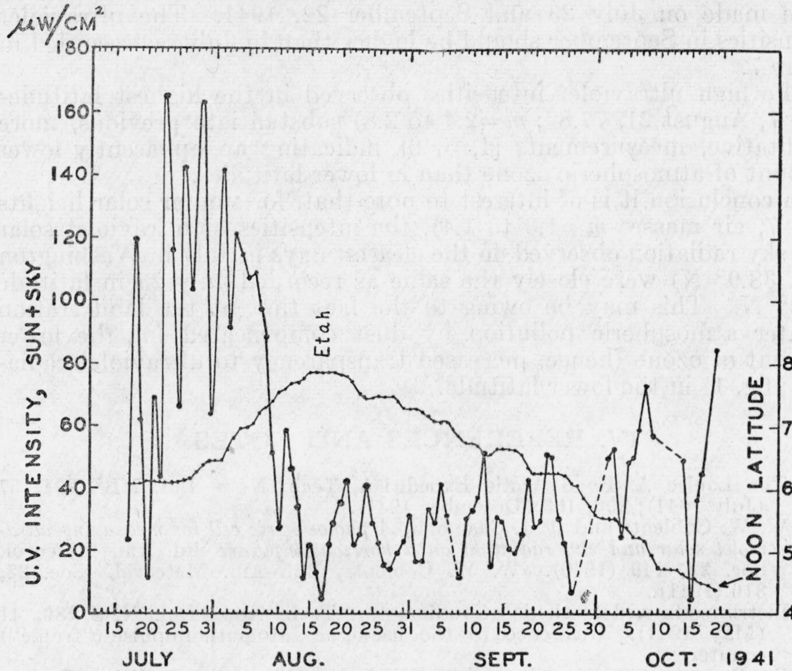

FIGURE 6.—*Graph showing the intensity of ultraviolet solar and sky radiation at the noon hour during the voyage.*

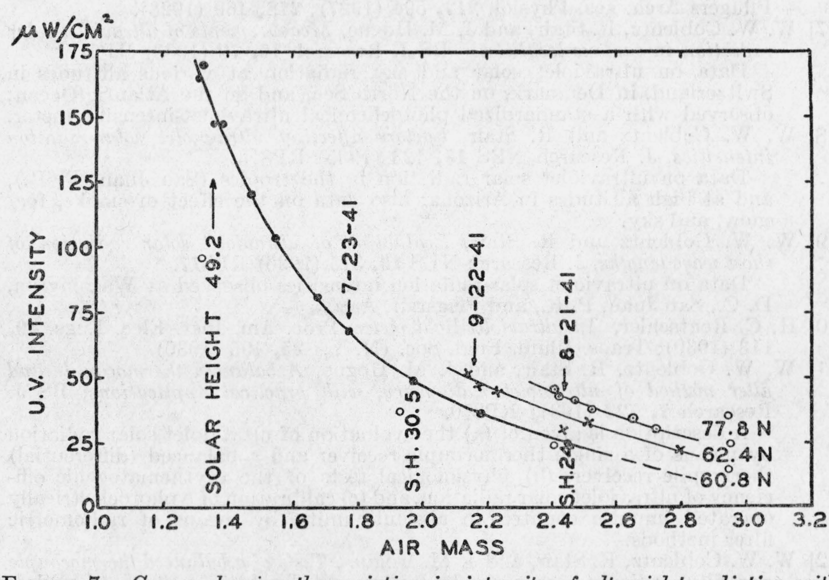

FIGURE 7.—*Curves showing the variation in intensity of ultraviolet radiation with solar height on three of the clearest days during the voyage.*

were made on July 23 and September 22, 1941. The ultraviolet intensities in September should be higher than in July, as recorded in figure 7.

The high ultraviolet intensities observed in the highest latitudes (fig. 7, August 21, 77.8°; $m=2.4$ to 2.8) substantiate previous, more qualitative, measurements [4, 5, 6], indicating an apparently lower amount of atmospheric ozone than in lower latitudes.

In conclusion it is of interest to note that, for similar solar heights (fig. 7, air masses $m=1.3$ to 1.4), the intensities of ultraviolet solar and sky radiation observed on the clearest days in July in Washington (lat. 38.9° N) were closely the same as recorded July 23 in latitude 60.8° N. This may be owing to the fact that at the land station greater atmospheric pollution by dust compensated for the lower amount of ozone (hence, increased transparency to ultraviolet radiation; fig. 1) in the lower latitude.

IV. REFERENCES AND NOTES

[1] The Louise A. Boyd Arctic Expedition, Tech. News Bul. NBS **291,** 57 (July 1941); **296,** 103 (December 1941).

[2] W. W. Coblentz and R. J. Cashman, *A photoelectric cell for measuring ultraviolet solar and sky radiation on a horizontal plane,* Bul. Am. Meteorol. Soc. **21,** 149 (1940). W. W. Coblentz, Bul. Am. Meteorol. Soc. **22,** 316 (1941).

[3] Instruments and methods of radiometry. Tech. News Bul. NBS **289,** 41 (May 1941). Reference to the use of an automatic impulse ("traffic") counter.

[4] F. Dannmeyer, *Die ultraviolette Himmelsstrahlung in nördlichen Breiten,* Strahlentherapie **35,** 607 (1930).

[5] F. Götz, *Zum Strahlungsklima des Spitzbergensommers,* Gerlands Beitr. Geophys. **31,** 119 (1931).

[6] O. Kestner and W. Borchardt, *Strahlenmessungen nördlich des Polarkreises,* Pflügers Arch. ges. Physiol. **217,** 504 (1927); **218,** 469 (1928).

[7] W. W. Coblentz, R. Stair, and J. M. Hogue, *Measurements of ultraviolet solar radiation in various localities.* BS J. Research **10,** 79 (1933) RP517.

Data on ultraviolet solar and sky radiation at various altitudes in Switzerland, in Denmark, on the North Sea, and on the Atlantic Ocean; observed with a standardized photochemical ultraviolet-intensity meter.

[8] W. W. Coblentz and R. Stair, *Factors affecting ultra-violet solar-radation intensities,* J. Research NBS **15,** 123 (1935) RP816.

Data on ultraviolet solar radiation in the tropics (San Juan, P. R.), and at high altitudes in Arizona; also data on the effect of smoke, fog, snow, and sky.

[9] W. W. Coblentz and R. Stair, *Evaluation of ultraviolet solar radiation of short wave lengths,* J. Research NBS **16,** 315 (1936) RP877.

Data on ultraviolet solar-radiation intensities observed at Washington, D. C., San Juan, P. R., and Flagstaff, Ariz.

[10] H. C. Rentschler, *An ultraviolet light meter,* Proc. Am. Inst. Elec. Engs. **49,** 113 (1930); Trans. Illum. Engl. Soc. (N. Y.) **25,** 406 (1930).

[11] W. W. Coblentz, R. Stair, and J. M. Hogue, *A balanced thermocouple and filter method of ultraviolet radiometry, with practical applications,* BS J. Research **7,** 723 (1931) RP370.

A description is given of (a) the evaluation of ultraviolet solar radiation by means of a single thermocouple receiver and a balanced (differential) thermopile receiver, (b) physiological tests of the erythematogenic efficiency of ultraviolet solar radiation, and (c) calibration of a photoelectrically operated impulse counter, in absolute units, by means of radiometric filter methods.

[12] W. W. Coblentz, R. Stair, and J. M. Hogue , *Tests of a balanced thermocouple and filter radiometer as a standard ultraviolet dosage intensity meter,* BS J. Research **8,** 759 (1932) RP450.

Data are given on the erythematogenic efficiency of ultraviolet radiation from various artificial sources and from the sun.

[13] W. W. Coblentz and R. Stair, *A portable ultraviolet intensity meter, consisting of a balanced amplifier photoelectric cell and microammeter*, BS J. Research **12,** 231 (1934) RP647.

[14] W. W. Coblentz and R. Stair, *A standard source of ultraviolet radiation for calibrating photoelectric dosage intensity meters*, J. Research NBS **16,** 83 (1936) RP858.

[15] W. W. Coblentz and R. Stair, *Evaluation of ultraviolet solar radiation of short wave lengths*, J. Research NBS **16,** 315 (1936) RP877.

Data are given showing a close agreement in the evaluation of ultraviolet solar radiation by means of: (a) a balanced thermopile [11] calibrated in absolute units by means of a standard of thermal radiation; and (b) a *Ti*-photoelectric cell [13] calibrated in absolute value, against a standard of ultraviolet radiation [14].

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