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Measurements of Solar Extreme Ultraviolet and X-Rays from Rockets by Means of a $CaSO_4$:Mn Phosphor

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The presence of solar extreme ultraviolet and x-rays at high altitudes in the atmosphere was detected by means of a thermoluminescent phosphor, $CaSO_4$:Mn, which was not sensitive to wavelengths above 1340A. Samples of the phosphor were flown in V-2 rockets and exposed to sunlight. By means of filters of Be, LiF, and CaF_2, response was measured in the wavelength bands 0–8A, 1050–1340A, and 1230–1340A. X-rays were observed on one flight which reached 128 km, during which a sudden ionospheric disturbance occurred. Wavelengths between 1050 and 1340A were observed on all four flights and reached as low as 80–90 km. A tentative value of 0.04 microwatt/cm^2 was calculated for the total intensity in the solar spectrum in the range 1050–1240A, which includes the Lyman alpha-line of hydrogen, at an altitude level somewhere between 82 and 127 km. A similar value for the range 1230–1340A was 0.02 microwatt/cm^2. A comparison of the responses of the phosphor strips flown without filters and those with filters indicated that radiation between 795 and 1050A reaches the region 82–127 km with an intensity well above that produced by a 6000°K blackbody sun.

INTRODUCTION

SINCE 1946, when V-2 rockets first became available for high altitude research, experimentation has been carried on to observe the solar spectrum to very short wavelengths in the ultraviolet by means of rocket-borne spectrographs. Previously, the limit of the known solar spectrum was 2863A.[1] Shorter wavelengths were prevented from reaching terrestrial or even balloon-carried equipment by the strong absorptions in the high atmosphere caused by the ozone layer and oxygen itself.

The known solar spectrum has now been extended[2,3] to 2100A by means of rocket-borne spectrographs. Despite numerous attempts, this limit has not been exceeded because of insufficient exposure. The time during which a spectrograph is nearly enough directed at the sun to obtain an intense exposure is severely limited by the roll and yaw of the rocket. It is hoped eventually to obtain exposures of a minute or more to full sunlight by means of sun-following stabilizing equipment or stable rockets.

A simple rocket-borne experiment to measure solar extreme ultraviolet-radiation and x-rays in several spectral bands without spectroscopic resolution was devised and carried out as an interim measure. The radiation detecting device used was a thermoluminescent $CaSO_4$:Mn phosphor having the unique property that it is sensitive to wavelengths below, but not above 1340A. After excitation the stored energy can be released as a visible luminescence by heating, and this gives a measure of the ultraviolet to which it was exposed. In order to use the phosphor to measure solar ultraviolet it was necessary to study its properties in detail and this work was reported in a separate paper.[4]

PENETRATION OF SOLAR RADIATION

The nature of the solar spectrum below 2000A is still a subject for much scientific speculation. A great intensity excess in the extreme ultraviolet over that from a blackbody at 6000°K has been proposed for many years and for various reasons. For example, in order to explain terrestrial magnetic storms and aurorae, Maris and Hulburt[5] suggested that solar flares provide an intensity 10^5 greater than that from a 6000°K blackbody in the region 500–1000A. To explain the coronal spectrum Edlen[6] showed that many of the lines can be accounted for by a temperature of the order of 10^6K. This temperature would give rise to significant intensities below 1000A and down to soft x-rays. Martyn and co-workers[7] suggested that radio fadeouts which occur simultaneously with solar flares are due to a sudden increase of ionization of oxygen in the D layer (30–80 km), brought about by increased intensity and penetration of solar ultraviolet, particularly the Lyman alpha-line, while others[8,9] suggested x-rays. Finally, the diurnal variation of ionization in the E and F regions indicates that the solar short wavelengths are present in the radiation from the normal sun in sufficient intensity to cause great changes in the conditions in the ionosphere.

Because of the lack of information on the solar spectrum below 2000A, the scanty knowledge of absorption coefficients, and the scarcity of reliable laboratory data on the various photochemical processes which may

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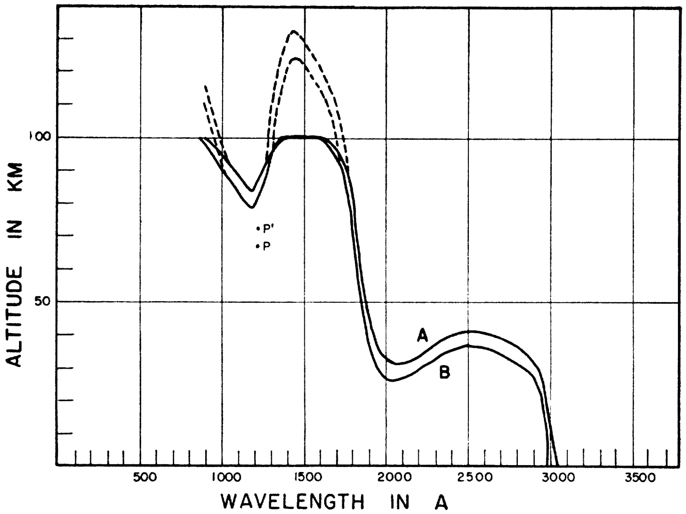

FIG. 1. Calculated altitudes at which the atmosphere above transmits one percent (curve B) and 10 percent (curve A) of the solar radiation for vertical incidence. *P* and *P′* are values for the Lyman alpha-line of hydrogen, based on absorption coefficients obtained by Preston.

occur in the upper atmosphere, there are still no completely acceptable theories of the ionosphere and of other phenomena occurring at altitudes above the ozone layer. It is generally accepted, however, that the process $O_2+h\nu\rightarrow O+O$ due to wavelengths less than 1750A occurs in the region 80–100 km[10,11] and that the various layers of the ionosphere are produced, at least in part, by ionization of nitrogen and oxygen by solar extreme ultraviolet, and that an excess over the radiation from a 6000°K blackbody is required.

Although the detailed processes responsible for creating the various regions of the ionosphere have received a great deal of attention, they are still not well established. For example, Wulf and Deming[10] suggested that the *E* layer is due to the ionization of O_2 by ultraviolet light (1012–910A). Hulburt,[12] on the other hand, proposed that soft x-rays are responsible for *E* layer ionization.

From laboratory data on the absorption spectra of atmospheric gases it is possible to calculate the approximate altitudes at which the various wavelengths in the solar spectrum may be expected to be encountered during the ascent of a rocket. The transmission of the high atmosphere for wavelengths down to about 2100A is now fairly well known. Below 2100A the data are not so well established. The approximate altitudes at which the atmosphere overhead transmits 1 percent and 10 percent of the solar radiation for vertical incidence were calculated and are shown in Fig. 1. Over most of the region the curves for the absorption coefficients are actually quite jagged, and only the mean values were taken for the calculation. In the region 1800–1300A the absorption coefficients for O_2 obtained by Ladenburg and Van Voorhis[13] were used; however, the application of these data to the upper atmosphere is confused by the theory of the dissociation of oxygen. In Fig. 1 the broken curves apply assuming no dissociation, and the solid curves apply if complete dissociation is assumed above 100 km and none below. To still shorter wavelengths there are only the estimates of Schneider,[14] and the curve is extended below 1000A by means of them. Nitrogen absorbs strongly below 795A (15.5 ev), but no quantitative data on its absorption are available. The pressure *versus* altitude data which were used were obtained by Havens, Koll, and LaGow.[15]

The Lyman alpha-line of hydrogen (1216A), which is of great astronomical interest, happens to fall in one of the deepest of the many narrow windows which cover this region. The data for the absorption of Lyman alpha by O_2 are in disagreement; Preston's[9] value differs from that of Williams[16] by a factor of 50. In Fig. 1, the altitudes for 1 percent and 10 percent transmission based on Preston's value for Lyman alpha (which is believed to be the more reliable) are indicated by points *P* and *P′*.

The exact altitudes at which measurable radiation can be detected depend on the radiation intensity present and the sensitivity of the detecting element as well as the atmospheric transmission. In Fig. 1, these factors are not taken into account, and only the transmission of the atmosphere is calculated. However, large changes in solar intensity or in receiver sensitivity produce relatively small changes in altitude, as can be seen from the fact that the displacement between the 10 percent and 1 percent transmission curves is small.

The conclusion from this calculation is that solar wavelengths below 1800A will not be encountered at altitudes below 80 to 100 km. A possible exception is

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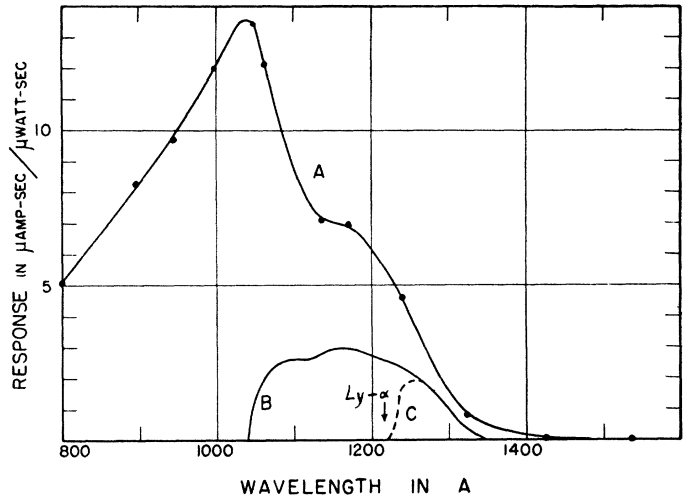

FIG. 2. Curve A is the spectral response of the $CaSO_4$:Mn phosphor calibrated against a thermocouple. Curves B and C are the response curves for the same phosphor with LiF and CaF_2 filters.

Lyman alpha, which, if present in the solar radiation as an emission line, may reach 60 km according to Preston.[9]

EXPERIMENTAL METHOD

Phosphor samples, which were sufficiently rugged to withstand a rocket flight and which could be given controlled heating electrically, were prepared by pressing the powder into nickel screens of 100 per inch mesh. The phosphor powder was bound in place by dipping into dilute Duco cement (5 percent Duco cement and 95 percent acetone). The thin coating of cement reduced the sensitivity of the phosphor to radiation in the region 1100–1300A by only about 10 percent, although Duco cement is quite opaque at these wavelengths in ordinary thin continuous films.

The energy stored in the phosphor, after excitation by short ultraviolet, was quickly released by heating, and the luminescence so produced was measured with a photomultiplier and recorder. Values of response were given in terms of an arbitrary unit, microamperes-sec, of integrated photomultiplier current.

The spectral response of the phosphor is shown in Fig. 2. For most practical purposes the response can be considered zero above 1340A. It was possible to make measurements in several restricted spectral bands in the extreme ultraviolet by placing suitable filters over the phosphor samples. The filters used were CaF_2, LiF, and Be. The curves showing the response of the phosphor through LiF and CaF_2 are also shown in Fig. 2, and were computed from transmission curves of the actual samples flown in flight (4). The bands covered and the filters used are given in Table I.

TABLE I. Wavelength bands obtained by filters.

Filter	Wavelength band
(1) CaF (1–3.4 mm)	1230–1340A
(2) LiF (1–2 mm)	1040–1340A
(3) Be (0.1 mm)	0–8A
(4) None	0–1340A
(5) LiF minus CaF_2	1040–1230A
(6) None minus (Be+LiF)	8–1040A

Bands (5) and (6) were obtained by the filter subtraction method, in which the responses measured through the various filters were subtracted from one another. For exact application, this method requires some knowledge of the relative intensity distribution in the radiation being studied and thus must await a spectrum photograph. It was, however, possible to obtain provisional information by the subtraction method by making certain assumptions concerning the nature of the solar spectrum.

The principal problem in the use of the phosphor was the avoidance of overheating the strips between exposure and measurement. Therefore, the experiment was included only in rockets flown in the winter months, an effort was made to recover the strips from the desert as quickly as possible, and they were shipped to Washington by air, packed in a thermos jug with ice.

As a check on the occurrence of excessive heating during flight and prior to recovery, control strips were included in each flight experiment. These strips were given standard exposures 4 to 12 hours prior to firing. The source used was a hydrogen discharge tube with a LiF window. Some of the control strips were kept in the laboratory at the White Sands Proving Ground and shipped to Washington together with the flight strips. Comparison of the thermoluminescence of the several control strips gave a measure of the loss in stored energy due to heating between flight exposure and shipment. This could be applied in some cases as a correction to the responses to sunlight measured in flight.

DETAILS OF THE SEVERAL ROCKET-BORNE EXPERIMENTS

During the period November, 1948, to February, 1950, six attempts were made with V-2 rockets to detect by means of the phosphor the presence of extreme ultraviolet and x-rays from the sun in the upper atmosphere. Four experiments were successful, while two failed as the result of severe explosions on impact. Dates of the flights and altitudes reached are given in Tables II and III.

In the first flight four units, each consisting of a steel block with 6 strips and filters, were mounted in the rocket midsection about $\frac{1}{2}$ in. inside the skin, and only partially protected from the windstream. The control strips showed that excessive heating occurred somewhere during the flight.

In flights (2) and (3), the strips were protected from the heating action of the air stream by being mounted on a cylinder which rotated inside a cylindrical cassette. They were exposed from just after fuel burn-out (60 sec) until just before warhead blow-off, a total time of 200 sec. This device solved the problem of excessive heating during flight.

In the fourth flight a phosphor of about 5 times increased sensitivity was used, and this made it possible to use five separate sets of phosphor strips. These were exposed successively during the rocket flight and measured the variation of radiation with altitude. There was only one set of filters and the strips were successively positioned behind them. Starting at 19 km each set of strips was exposed for 50 seconds. The spectral transmission of the LiF and CaF_2 filters was measured, and the absolute spectral sensitivity of the phosphor was known from measurement against a thermocouple.[17] Although the flight was successful, the impact was exceptionally severe and only 10 of the 50 strips flown were recovered. These strips, however, gave quantitative results.

The exposure during flight depended on the roll and yaw of the rocket. On flight (1) this was estimated, and on flights (2) and (3) it was measured by means of a photographic film covered with a dense filter. On the fourth flight good aspect data were available and made possible calculation of the exposure to about 30 percent accuracy.

RESULTS

The numerical response data are presented in Tables II and III. The first experiment, because of the loss in response due to heating, was only qualitative. The fourth flight, however, gave data of sufficient accuracy to warrant energy calculations.

1. X-Rays

The response through beryllium observed on February 17, 1949, is definite evidence of soft x-rays, presumably of solar origin. Since the transmission of the beryllium filter reached a very small value at 10A, the x-rays observed must have been of wavelengths shorter than 10A and most probably were shorter than 8A. Previous to this firing the presence of x-rays was detected by Burnight,[18] who used a Schumann photographic plate covered with Be and flown on August 5, 1948.

TABLE II. Data obtained from experiments 1, 2, and 3.

Experiment	1	2	3
Time of firing (MST)	November 18, 1948, 3:34 P.M.	February 17, 1949, 10:00 A.M.	April 11, 1949 3:05 P.M.
Maximum height attained in km above sea level	146	128	88
Height during exposure in km	1–146–1	49–128–86	54–88–17
Estimated "effective" exposure time in minutes	1.5	1	0.5
Phosphor area in cm^2	1.61	1.61	0.65
Solar activity during flight	Normal	Sudden ionospheric disturbance	Normal
Thermoluminescence of recovered strip in microamp-sec			
with Be filter ($<8A$)	Doubtful	0.10	0.000
with LiF filter (1040–1340A)	0.01	0.52	0.008
with CaF_2 filter (1230–1340A)	0.005	0.29	0.000
with no filter ($<1340A$)	0.05	1.14	0.034
Control strip flown ÷ control strip grounded	0.014	0.19	0.23

Only on our second flight, which reached 128 km, were x-rays definitely detected. It is interesting to note that a sudden ionospheric disturbance occurred during this flight. X-rays were not positively recorded on flight (1), although the maximum altitude reached was 146 km, nor on flight (3), maximum altitude 88 km. On these flights ionospheric conditions were normal.

There were small indications of x-rays on the fourth flight, but they appear contradictory because the value from 19–82 km exceeds that from 82–127 km. It is entirely possible that solar x-rays are emitted from the sun in bursts and may vary during a flight; but until evidence of this sort is repeated, we do not consider it conclusive.

2. Penetration of the Band 1050–1340A

Solar radiation of wavelengths between 1050 and 1340A was observed to reach levels in the atmosphere between 80 and 90 km. This can be seen from Tables

TABLE III. Data obtained from experiment 4.

Time of firing: February 17, 1950, 11:01 A.M. MST
Maximum height attained: 150 km above sea level
Solar activity during flight: No flares or sudden ionospheric disturbance observed
Phosphor area 0.65 cm^2

Exposure position	1	2	3
Height during exposure in km above sea level	19–82	82–127	127–148
Effective exposure time in sec	1.5	3	3
Thermoluminescence of recovered strip in microamp-sec			
with Be filter 0.1 mm ($<8A$)	0.040	0.024	damaged
with LiF filter 1.5 mm (1040–1340A)	0.012	0.126	damaged
with CaF_2 filter 1.6 mm (1230–1340A)	damaged	0.019	damaged
with no filter ($<1340A$)	0.073	5.84	8.87
Control strip flown ÷ control strip grounded	damaged	0.79	0.91

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[18] T. R. Burnight, Phys. Rev. **76**, 165 (1949).

II and III. In experiment 3 a positive response was obtained for the LiF-covered strip, and the highest altitude reached was 88 km. In experiment 4, exposure 1, a response was recorded for the LiF-covered strip and the maximum altitude reached during the exposure was 82 km. This result was expected from theoretical grounds; as shown in Fig. 1, one percent of the incident radiation in the wavelength range 1000 to 1300A, on the basis of laboratory measurements of the transmission of air, would penetrate to 90 km or lower.

3. Penetration in the Band 1240–1340A

In the spectral band 1240–1340A considerable intensity was observed in experiment 2 for the altitude range 49–128–86 km, and in experiment 4, for the altitude range 82–127 km. In absolute value the response in experiment 2 was greater than in experiment 4 because the exposure time above 90 km was much greater, owing to the fact that the exposure covered the entire top of the trajectory. For the altitude range below 88 km, covered in experiment 3, no response in this band was recorded. Thus, the penetration altitude for radiation between 1240 and 1340A appears to lie somewhere between 90 and approximately 125 km. This result is reasonable, theoretically, since the absorption data for oxygen, as shown in Fig. 1, indicate that 1340A penetrates (1 percent) to 100 km and 1240A to 82 km.

TABLE IV. Comparison of responses observed in experiment 4 with values calculated for a blackbody.

	6000°K BB	5000°K BB	Observed
R with LiF (μa-sec)	3.8	0.082	0.25
R with CaF$_2$ (μa-sec)	2.1	0.052	0.04
Ratio	1.8	1.6	6.6

4. Penetration in the Band 795–1050A

The radiation in the band 795–1050A can be obtained approximately by subtracting from the bare phosphor response (0–1350A), the responses through Be (0–10A) and through LiF (1050–1350A), after making correction for the filter transmission. The radiation below 795 was presumably largely absorbed by N$_2$ at all altitudes reached in these flights. Furthermore, the phosphor sensitivity, as indicated by Fig. 2, became rapidly decreased below 1050A. Soft x-rays above 10A may have contributed a small amount to the observed response, however.

There is good evidence, from flight (4), exposure 2, that wavelengths from 795 to 1050A were present in considerable intensity in the altitude range 88–127 km, for the response of the bare strip was nearly 50 times that of the strip covered with LiF, and the x-ray response was so small as to be doubtful. From exposure 1 on this flight there is some evidence that radiation in this band penetrates below 88 km; however, the bare strip response was only 6 times the LiF-covered response; this was so close to the 3 times reduction expected because of the transmission of LiF that the conclusion is not regarded as positive.

The response of the bare strips in experiment 4 over the range 127–148 km was 50 percent greater than from 82–127 km, and the effective exposure times were approximately equal. This is compatible with the idea that most of the radiation as seen by the bare phosphor penetrates with little absorption to 127 km, but becomes absorbed in the interval 88 to 127 km. For altitudes above 127 km, it can be seen from Fig. 1 that there is little attenuation by air, especially if the oxygen is dissociated.

CALCULATION OF SOLAR EXTREME ULTRAVIOLET INTENSITIES

Certain numerical values of solar radiation intensity can be calculated from the data obtained in experiment 4 because the phosphor and filters used in this flight were calibrated and a good record of the rocket motion during the exposures was available.

The total measured response of the phosphor, R, may be expressed by the following equation:

$$R=\int_{\lambda_1}^{\lambda_2} H_\lambda S_\lambda T_\lambda d\lambda \int A(\theta, \phi)dt, \qquad (1)$$

where H_λ is the solar spectral intensity. S_λ is the sensitivity of the phosphor and was known. The filter transmittance T_λ was measured for normal incidence, and corrections for departures from normal incidence could be neglected because of the relatively small field of view. The function $A(\theta, \phi)$ is the area of phosphor normal to sunlight, and the second integral gives the total effective exposure and was calculated from data on the rocket aspect during flight. It was possible to solve Eq. (1) approximately for the total energy over the band 1050–1240A. This could be done without knowing the detailed nature of H_λ because $S_\lambda T_\lambda$ is nearly constant over this wavelength interval, as shown in Fig. 2.

The total radiation $\int H_\lambda d\lambda$ for the band 1050–1240A, computed in this way, was 0.04 μw/cm^2. This value applies for the altitude range 82–127 km, and is considered correct within a factor of 2. The value completely above all absorbing gases would be somewhat, but probably not greatly, higher because, as shown in Fig. 1, this wavelength band is transmitted without great attenuation to 90 km.

A calculation was also made for the energy within the band 1230–1340A recorded by the CaF$_2$ filter and phosphor. In this case $S_\lambda T_\lambda$ cannot be considered constant over the wavelength interval. It is necessary to make some assumption concerning the nature of H_λ. Making the simplest assumption possible, that H_λ is constant over this narrow interval, the result for total energy was 0.02 μw/cm^2. The accuracy of this result is low because the original datum from which it was computed is small and therefore, subject to considerable error, and because the nature of the spectrum is unknown over this interval.

We shall now consider several possible assumptions concerning the detailed nature of the solar intensity distribution in the neighborhood of Lyman α and see whether the observed data favor one or the other picture of the spectrum. The first assumption is that the spectrum is a blackbody, and that Lyman α is not important either in emission or absorption. The second assumption is that most of the energy in the region 1040–1340A is concentrated in Lyman α in emission. The third assumption is that the spectrum is described by a blackbody, with Lyman α a strong and broad absorption line with a narrow and intense emission line at its center.

The assumption of a pure blackbody distribution can be shown to be in poor agreement with the data over the range 1040–1340A. In Fig. 3, curve A represents a 6000° blackbody distribution, while curves B and C show the response of the phosphor, $H_\lambda S_\lambda T_\lambda$, to this radiation with LiF and CaF$_2$ filters, respectively. Numerical values of response through the filters and of the response ratio were calculated for 6000°K from these curves, and similarly for 5000°K, and are given in Table IV. The calculated response ratio is below 2 and does not change rapidly with temperature while the observed ratio is between 6 and 7.

The assumption of a pure emission line, on the other hand, does not agree with the experimental data, because, for any reasonable half-width, no energy should be present in the spectral range 1230–1340A. In flights (1), (2), and (4) definite responses were obtained in this spectral range.

Thus the true situation must be more complicated, and it is probable that the spectrum is a continuum upon which Lyman α is superimposed as a wide absorption line with a narrow emission line at its center.

The intensity of solar radiation in the band 795–1050A can be shown, from the data of flight (4), to be well above that produced by a 6000°K blackbody sun. The response in this band was calculated from exposure 2 by subtracting the Be- and LiF-covered strip exposures from the bare strip exposure, after correcting for the filter transmission and the decay of stored energy. The quantum efficiency of the phosphor with respect to thermoluminescence was 5 to 10 percent at 1050A and about half as much at 800A. From these data it was estimated that the flux was between 5×10^{11} and 3×10^{12} quanta per cm^2 per sec. If the sun is taken as a blackbody at 6000°K, the flux for wavelengths below 1050A would be 2.3×10^{10} quanta per cm^2 per sec. Thus, the observed radiant intensity at 82–127 km was one to two orders of magnitude greater than that expected from a blackbody at 6000°K.

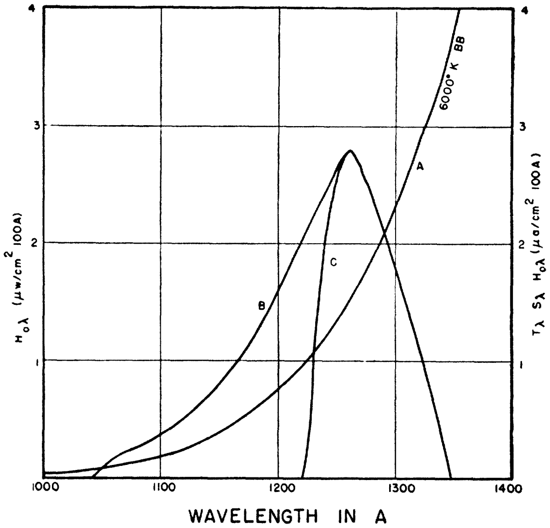

FIG. 3. Curve A is the spectral intensity distribution for a 6000°K blackbody sun. Curves B and C are the calculated response curves for the CaSO$_4$:Mn phosphor with LiF and CaF$_2$ filters, respectively, when exposed to the 6000°K blackbody spectrum.

Our thanks are due Mr. John R. Pierce of the New Mexico College of Agriculture and Mechanic Arts, who carried out the installation and calibration work at the White Sands Proving Ground. We wish also to express appreciation to Professor Theodore Lyman, who was among the first to suggest flying this phosphor in rockets and who has followed the course of this work with great interest.