a field-theoretical situation is completely determined if on a three-dimensional hypersurface the canonical variables are given in such a manner that all the constraints (which are finite in number at each point) are satisfied and a hamiltonian has been chosen for all of space-time. In that case, the solutions are unique and do not permit even a coordinate transformation. A coordinate transformation which leaves the initial situation unchanged is equivalent to the adoption of a new hamiltonian away from the initial hypersurface.

In attempting to quantize this type of theory, we can simplify our problem by first carrying out a canonical transformation that converts the primary constraints into canonical momentum densities. As for the secondary (and higher, if necessary) constraints, it appears that their conversion is neither easy in practice nor desirable, because in singular regions the secondary constraints may not be satisfied. Once we have found a proper formulation for the singular regions, the "sources" and "sinks" of the vacuum field, the examination of the quantized covariant theory can be undertaken in earnest.

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Photon Counter Measurements of Solar X-Rays and Extreme Ultraviolet Light

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Data telemetered continuously from photon counters in a V-2 rocket, which rose to 150 km at 10:00 A.M. on September 29, 1949, showed solar 8A x-rays above 87 km, and ultraviolet light around 1200A and 1500A above 70 km and 95 km, respectively. The results indicated that solar soft x-rays are important in E-layer ionization, that Lyman α-radiation of hydrogen penetrates well below E-layer, and that molecular oxygen is rapidly changed to atomic above 100 km.

A V-2 ROCKET, fired in September 1949, carried a set of photon counter tubes which were sensitive to light in the soft x-ray and extreme ultraviolet regions of the spectrum. Each tube responded to a relatively narrow portion of the spectrum in one of four bands covering 0–10A, 1100–1350A, 1425–1650A, and 1725–2100A. The experiment provided an uninterrupted telemetered recording of solar radiation intensities within these wavelength bands throughout the flight of the rocket. Intense solar x-ray emission was detected at altitudes above 87 kilometers. In the atmospheric window near λ 1200A, the photon counters responded strongly above a level of about 70 kilometers. Most of the solar radiation near the peak of the Schumann-Runge absorption band of molecular oxygen, was absorbed between the levels of approximately 95 and 115 km. Only one tube was flown which was sensitive to the longer wavelengths between the oxygen and ozone bands ($\sim$2000A). Its counting rate rose sharply when the rocket reached an altitude of 7 kilometers, but the tube was too sensitive to provide any useful data above 20 kilometers. These measurements support the ideas: that E-layer ionization is directly related to soft x-ray emission from the corona; that Lyman α-radiation penetrates the atmosphere well below E-layer; and that the transition from molecular to atomic oxygen takes place at altitudes near 100 km.

FLIGHT DETAILS

The rocket (V-2, No. 49) was fired at 10:00 A.M., M.S.T. on September 29, 1949 at the White Sands Proving Ground, New Mexico. The altitude of the sun was 43 degrees. No unusual solar activity was noted at the time of the flight. The telemetering record was continuous over the entire flight period of 336 seconds, during which time the rocket soared to a height of 150 km. Fuel cutoff was made at 64 seconds after take-off. For the first 60 seconds the rocket was in stable flight, after which time it developed a slow, steady roll of approximately 12 seconds average period. The roll persisted until the warhead was blown off at 336 seconds.

EXPERIMENTAL DETAILS

An assortment of 6 photon counter tubes was contained in two pressurized boxes, each unit comprising in effect a photon counter spectroscope. The boxes were located on opposite sides of the warhead, with exposed window areas parallel to the surface of the warhead. In addition to the counter tubes, each box also contained one control tube, sensitive only to cosmic rays, and one photocell for determining the roll orientation of the rocket with respect to the sun.

Each tube consisted of a chrome-iron cathode cylinder, $\frac{3}{4}$ inch in diameter and 2 inches long, and an anode wire, 0.025 inch in diameter. The cathode also served as the envelope of the tube. Glass caps, which supported the anode wire, were sealed to the steel cylinder at each end. A circular aperture $\frac{3}{16}$ in. in diameter was provided in a flat recess, milled midway along the length of the cathode. This aperture was covered by

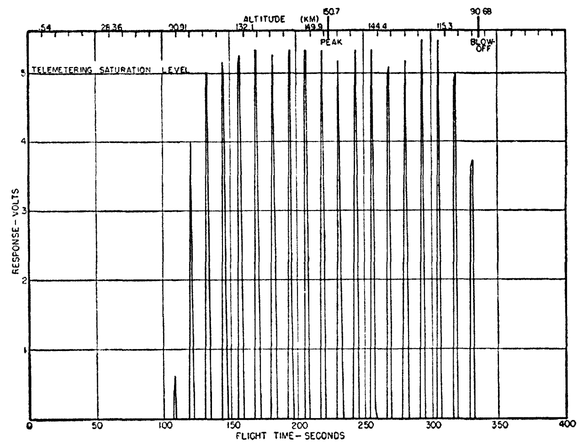

FIG. 1. A plot of data read directly from the telemetered record of the counting rate of an x-ray photon counter. The sharp responses occurred each time the spinning rocket presented the tube to the sun. The telemetered signals were not continuous, but the commutation rate was rapid enough to provide about eight points per exposure. In the illustration, smooth curves are drawn through the experimental points.

an appropriate window material, cemented to the steel body.

The counting rate produced in each tube, when excited by radiation, was determined indirectly by integrating the flow of charge through the tube in an RC circuit of 2 seconds time constant, thereby producing an average dc voltage proportional to the counting rate. The resultant voltage was then impressed on a cathode follower stage, from where it was coupled to the telemetering system. Sufficient voltage was obtained with this simple means of charge integration to satisfy the telemetering requirements, without the necessity of additional amplification. Data originating in all tubes was handled over four telemetering channels by resorting to time sharing mechanical subcommutation.

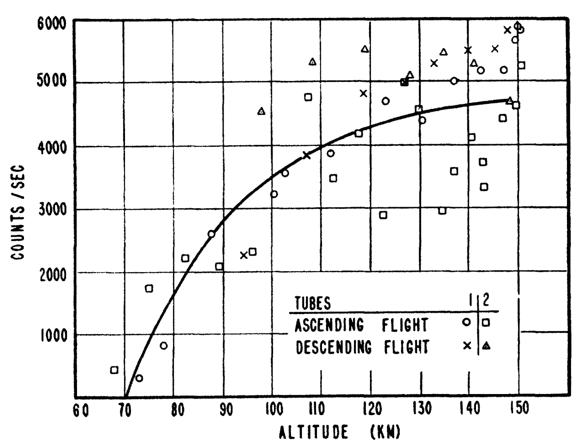

FIG. 2. Intensities measured with two nearly identical photon counters in the 1100A–1350A wavelength band. Four sets of points are plotted representing the telemetered data of the two tubes, corrected for saturation and effect of time constant, in ascending and descending portions of the rocket flight.

Figure 1 is a plot of data read directly from the telemetering record and is representative of the type of record observed for most of the tubes used in the experiment. With every rotation of the rocket, the tube swept through one exposure to the sun. Above 100 km the intensities were strong enough to produce saturated responses with each exposure. The most serious factor affecting the accuracy of the measurements was the error involved in extrapolating these saturated indications. In order to estimate the true maximum intensities, it was assumed that the shape of the response curve was dependent only on the geometrical relationship between the sun and the counter tube window. On this basis, the fraction of the maximum response at any given time earlier or later than the instant of maximum exposure could be determined by examining the shapes of the first few undistorted responses. The corrected maxima were then estimated from measurements made on the slopes of the curves at selected fractions of maximum exposure. In most cases the largest corrections computed in this way brought the true maxima up to twice full scale indication of the telemetering circuit. A second correction was applied to the data to compensate for the effect of time constant in the counter tube circuit. The speed of rotation of the rocket was great enough so that the time of exposure of each tube to the sun was comparable to the time constant of the RC circuit.

In addition to its axial spin, a certain amount of precessional motion is always imparted to a rocket. The yaw angle of the precessional motion of a V-2 rocket has in several high altitude flights been as great as 20 degrees. Since the angular field of view of each photon counter tube was limited to approximately ± 30 degrees about the normal to the window and was not flat over this range, the aspect of the rocket had an influence on the photon counter response. Insufficient aspect data was obtained in this flight to permit complete aspect corrections, but fortunately the flight of V-2 No. 49 appeared to be unusually stable.

Figure 2 is a plot of four sets of data representing the ascending and descending flights of two identical photon counters. To a large degree the scattering of the points may be related to the uncertainties in extrapolating the saturated exposures, and to lack of sufficient rocket aspect information. It would be unjustified to attribute a reliability greater than roughly plus or minus 50 percent to the corrected counting rates. In spite of the scattering of the individual points on the curves, however, certain features of the measurements in three of the four wavelength bands were still quite well defined, such as the level of maximum penetration of the solar radiation and the altitude of maximum rate of absorption.

ULTRAVIOLET PHOTON COUNTERS

The counting action of an ultraviolet photon counter is essentially the same as that of the self-quenching

Geiger counters ordinarily used for detection of x-rays and gamma-rays. The primary electrons which trigger the Townsend avalanches of the discharge are photoelectrically ejected from the surface of the cathode wall.

In contact with gases such as are commonly used in Geiger counters, the photoelectric thresholds of metal surfaces generally fall in the ultraviolet below 3000A. While studying the effects of traces of electronegative gases in Geiger tube fillings, the authors observed a marked increase in the photoelectric work function. An extreme depression of the threshold wavelength occurred when the halogen gases, Cl_2 or Br_2, or halogenated hydrocarbons such as methylene bromide were included in the gas mixture. In the latter case all trace of photosensitivity above 1100A could be eliminated when the partial pressure of the vapor exceeded 1 mm Hg. Since the short wavelength limit of photosensitivity could be controlled by choosing a window from materials such as lithium fluoride, sapphire, quartz, potassium chloride, or Vycor glass, it was possible to make tubes with spectral responses limited to bandwidths of only a few hundred angstroms in the extreme ultraviolet.

Figure 3 shows the spectral response curves of three types of ultraviolet photon counters used in the rocket experiment. The ordinate scales were arbitrarily chosen to permit their combined presentation in one figure. The spectral measurements were carried out with a vacuum monochromator of the type described by Tousey, Johnson, Richardson, and Toran.[1] To derive the indicated efficiencies, comparisons were made of photon counter measurements and thermocouple measurements[2] of the hydrogen arc discharge. At first glance it might appear that the quantum efficiencies, ranging from 10^{-6} to 10^{-8} count per quantum, are extremely low. It should be noted, however, that the wavelength of the peak response for each tube is very close to threshold because of the sharp cut-off characteristics of the window materials on the short wavelength side. If the responses were measured independently of the effect of window absorption, the efficiencies would most likely rise to values of the order of 10^{-4} count per quantum at shorter wavelengths.

The cathodes of all three photon counters were made of chrome-iron. Tube (*A*), with a threshold at 1350A, was filled with 15 mm Hg of Cl_2 and 300 mm Hg of neon, and had a lithium fluoride window which was transparent to about 1100A. An admixture of one-half millimeter of bromine in 300 mm Hg of neon was used in tube *B*, to produce a peaked response at 1500A. The cutoff at 1425A was the limit of transmission of the synthetic sapphire window. A mixture of 10 mm Hg of ethylene and 10 mm Hg of argon yielded the long wavelength characteristic of tube *C*. Its cutoff at 1725A was produced by a crystalline quartz window.

[1] Tousey, Johnson, Richardson, and Toran, J. Opt. Soc. Am. **40**, 264 (1950).

[2] D. M. Packer and C. Lock, J. Opt. Soc. Am. **40**, 264 (1950).

At the time the photon counter tube experiment was proposed for V-2 No. 49, relatively little information had been accumulated about the stability of photon counters for the extreme ultraviolet. It was recognized that the spectral sensitivity altered with aging and with use. Until the very latest stages of preparation for the rocket-experiment, the grating monochromator was not available for detailed studies of the aging characteristics and the rough outlines of the regions of spectral sensitivity were determined by the use of filters.

The schedule of the experiment involved a delay of about one month between final assembly of the tubes in the warhead at NRL and the actual firing at White Sands. As a result it was not possible to check accurately the spectral responses of the tubes at the time of firing. On the basis of tests continued on control tubes at NRL, after shipment of the warhead from NRL to White Sands, it appeared that the tubes for the 1150–1350A band remained virtually unchanged over a period of several months. However, the thresholds of most of the

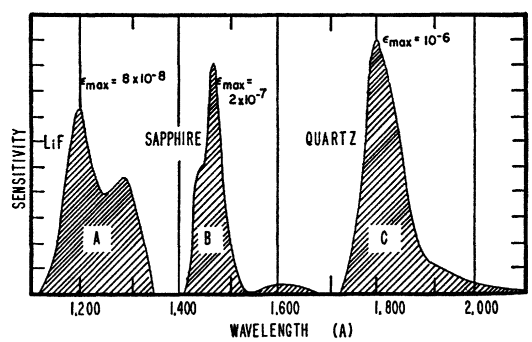

FIG. 3. Spectral response curves of three types of ultraviolet photon counters used in the rocket. The maximum photoelectron yields, ϵ_{max}, for each tube are indicated in units of counts per quantum.

tubes in the longer wavelength bands exhibited a tendency to drift to longer wavelengths. At the time of firing, various rough tests could be made of the reliability of the tubes. For example, the tubes assembled in the warhead were exposed to a hydrogen arc and their responses observed when various filters were inserted and as the air path between the arc and the tubes was varied. It was concluded from such checks that the tubes finally selected to be flown in the rocket had not undergone serious changes in characteristics. At best, however, the efficiencies of the rocket tubes could not have been known to better than an order of magnitude at the time of firing.

X-RAY PHOTON COUNTERS

Two of the photon counters were equipped with beryllium windows 0.005 inch thick, to pass soft x-rays. The transmission of the beryllium window was almost perfect at 2A, but dropped to 10 percent at 6.5A, one percent at 8.5A, and 0.1 percent at 9.5A. Beyond 10A, the window was virtually opaque. The mechanism of

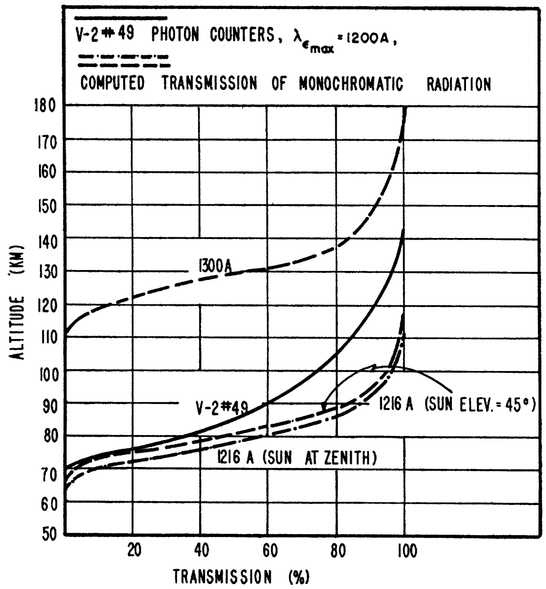

FIG. 4. Penetration of the atmosphere by ultraviolet radiation in the 1100A–1350A spectral region. The solid line is obtained from the data of two photon counters. The dashed line curves were computed from published absorption coefficients (references 4 and 5) at λ1216A and λ1300A for a sun elevation of 45 degrees. The dot-dash curve was computed for the sun at its zenith.

x-ray photon counting differs from that for ultraviolet photon counting in that the x-ray photons transmitted by the window are absorbed almost completely by photoelectric effect in the gas filling of the tube. If it is assumed that each photoelectric absorption of an x-ray quantum produces a discharge of the counter tube, the quantum counting efficiency may be taken as simply the product of the beryllium transmission and the percentage of the photons absorbed in the gaseous volume of the tube. Such an assumption is valid for the majority of counting gas mixtures which use a rare gas in combination with a hydrocarbon quenching vapor. If an electronegative gas impurity is present, however, a certain fraction of the absorbed quanta will fail to produce counts.[3] This effect is especially prominent when a halogen gas is admixed with a rare gas. In the tubes used in the rocket, about one-fifth of the quanta penetrating the beryllium window were effective in triggering counts.

MEASUREMENTS OF EXTREME ULTRAVIOLET RADIATION

All of the photon counters used in the rocket were somewhat too sensitive and produced off-scale signals as the rocket approached the peak of its flight. In the longest wavelength band (~2000A), the degree of saturation was so great as to prevent any reasonable extrapolation of the early portion of each response to the sun. The original set of tubes for the rocket included a second tube with identical spectral response, but having only one-tenth the window area, so as to cover a higher intensity range. Unfortunately this tube failed before the flight. In the shorter wavelength bands, the tubes did not suffer from such extreme saturation. The estimated true maxima were about twice the full scale indication of the telemetering circuit, and were obtained by extrapolating the lower portions of each curve of counting rate relative to angle with respect to sun.

Figure 2 is a plot of all the data obtained from two photon counters, type *A*, sensitive in the 1100–1350 angstrom region. The two tubes were located diametrically opposite each other in the rocket warhead so that their maximum responses to the sun were 180° apart. Although the individual points scattered rather widely, the lowest altitude at which appreciable intensity was detected was defined within ±5 km at about 70 km, and the average curve for the four sets of points approached a maximum asymptotically, near the top of the flight. In Fig. 4 the solid line represents the rocket data. The broken line curves were computed for an atmosphere of uniform composition of molecular oxygen and nitrogen up to the highest altitude, using the absorption coefficient of molecular oxygen at λ1216A reported by Preston[4] and the absorption measurements of Ladenburg and van Voorhis[5] at the

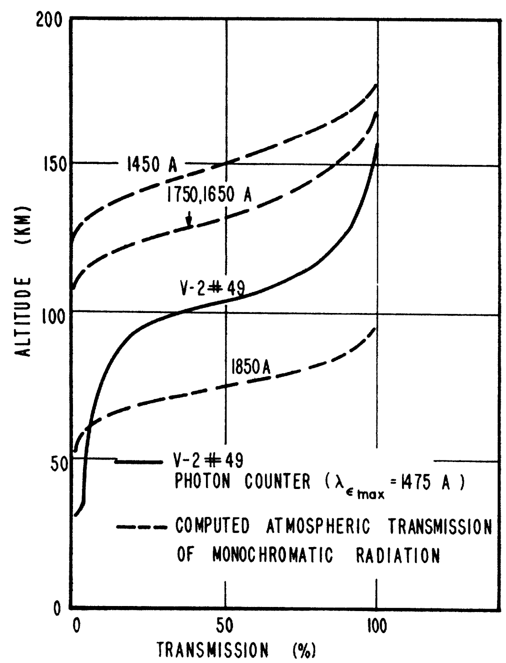

FIG. 5. Penetration of the atmosphere by ultraviolet radiation in the neighborhood of λ1500A. The solid line is obtained from rocket measurements made with tube *B* of Fig. 3. The broken line curves were computed from absorption data of reference 5. Data for λ1750, and λ1650A, on either side of the absorption maximum at λ1450A, almost coincide and are drawn as a single curve.

[3] H. Friedman, Proc. Inst. Radio Engrs. **37**, 791 (1950).

[4] W. M. Preston, Phys. Rev. **57**, 887 (1940).

[5] R. Ladenburg and C. C. van Voorhis, Phys. Rev. **43**, 315 (1933).

longer wavelength. Atmospheric pressure data used were those reported by Havens *et al.*[6]

The maximum depth of penetration indicated by the experimental curve is in agreement with computations for the Lyman alpha-line of hydrogen. Since the photon counter was also sensitive to wavelengths as long as 1350 angstroms the slope of the experimental curve toward the characteristic computed absorption level for λ1300A may be indicative of a response to longer wavelength radiation than the Lyman alpha-line at greater altitudes.

The solid line of Fig. 5 shows the average of the ascending and descending rocket measurements of one photon counter, type *B* (Fig. 3), sensitive to wavelengths in the neighborhood of 1500A, where the absorption coefficient for molecular oxygen is a maximum. The broken line curves were computed for an atmosphere of unaltered composition containing only molecular oxygen and nitrogen up to the highest altitudes. The rapid rate of absorption of radiation, observed in the region of 100 kilometers altitude, is indirect evidence of a rapid transition from molecular to atomic oxygen at that level. Otherwise, the maximum rate of absorption should have occurred at about 145 km, as shown in the computed curve for λ1450A. An unexplained feature of the experimental curve was the small response detected down to levels as low as 50 kilometers. This could perhaps be blamed on the electronics by attributing the early response to some form of electrical crosstalk or commutator noise, but interference tests made just prior to firing showed no signs of such imperfections in the system.

In the longest wavelength band, 1750–2100 angstroms, the photon counter sensitivity was so high that no true intensities could be estimated above 20 kilometers. Radiation in this band was detected at 7 kilometers above sea level and complete saturation developed after only three rotations of the rocket.

Without knowing the detailed features of the spectrum of solar radiation in the ultraviolet, it is impossible from the photon counter measurements to compute the energy flux of radiation incident on the atmosphere. If it is assumed that the source of ultraviolet radiation is a blackbody, then measured intensities in the bands centered at 1200A and 1500A indicated sun temperatures of the order of 6000°K and 4500°K at the respective wavelengths. To a rough approximation, the rocket measurement indicated a flux of from one to ten ergs per cm^2 per second in the 1150-1350A band. This result agrees in order of magnitude with the flux measured by Tousey, Watanabe, and Purcell, using a thermoluminescent phosphor.

X-RAY MEASUREMENTS

The solid line curve of Fig. 6 represents the averaged x-ray measurements of two photon counters equipped

[6] Best, Durand, Gale, and Havens, Phys. Rev. **70**, 985 (1946).

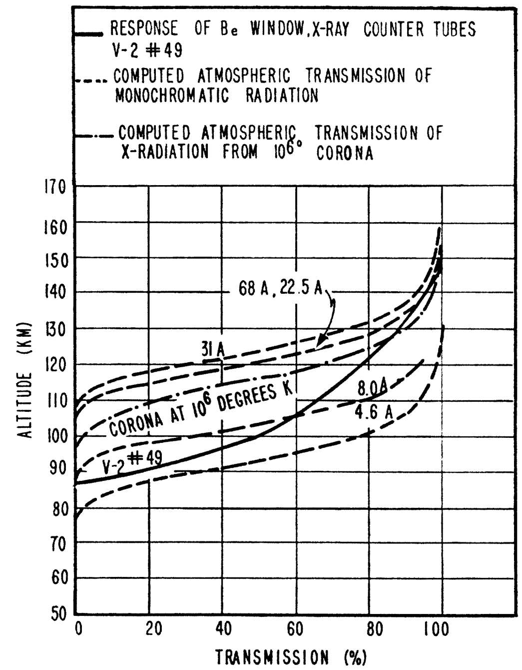

FIG. 6. Penetration of the atmosphere by soft x-rays. The dashed line curves were computed from absorption data listed in Compton and Allison (reference 7) and the pressure data of Havens, *et al.* (reference 6). Because the *K* critical absorption limits of oxygen and nitrogen fall at 23.6A and 32.2A, respectively, the penetration of longer wavelengths is comparable to that of shorter wavelengths, as is shown by the superposition of curves for λ68A and λ22.5A. The dash-dot curve was computed from the spectrum of reference 12. The solid line curve was obtained from the averaged data of two photon counters flown in the rocket.

with beryllium windows. Using Havens' pressure data, the transmission of soft x-rays by the upper atmosphere was computed[7] for several wavelengths between 4.6A and 68A. In these computations, illustrated by the broken line curves of Fig. 6, it was assumed that absorption could be attributed entirely to oxygen and nitrogen and that the relative atomic concentration of these elements did not vary with altitude. A significant feature of these curves is the relatively narrow altitude spread within which x-rays of a wide range of wavelengths are absorbed and the approximate coincidence of this altitude region with *E*-layer. The fact that the rocket-borne photon counters detected no x-rays at altitudes below 87 kilometers can be taken as evidence that the high energy limit of the x-ray spectrum occurred at approximately five to seven angstroms. From the observed counting rates at the peak of the flight, the computed flux of x-rays incident on the atmosphere amounted to about 10^{-4} erg per cm^2 per sec. The production of *E*-layer requires between 10^{-2} and 10^{-1} erg/cm^2/sec. Since the beryllium window was essentially opaque above 10A, and since the limit of the x-ray

[7] A. H. Compton and S. K. Allison, *X-Rays in Theory and Experiment* (D. Van Nostrand Company, Inc., New York, 1947), 2nd ed.

spectrum appeared to fall at about 5–7A, the entire x-ray response obtained in the experiment could be attributed to a narrow band centering about a wavelength of 8 angstroms and probably constituting only a small portion of the entire solar x-ray spectrum.

That x-rays from the sun may cause the ionization of *E*-region was first brought out by Hulburt.[8] The idea was later developed in considerable detail by Bates and Hoyle,[9] who derived the spectrum of x-rays necessary to produce the observed *E*-layer. Taking into account all the details of the conversion of x-ray energy to ionization, best agreement with the altitude distribution of *E*-layer ionization was obtained with an x-ray spectrum having a maximum in the neighborhood of 325 ev. Experimentally, there are now several sources of evidence for the emission of x-ray quanta from the solar corona. For example, Edlén[10] identified many of the coronal emission lines with forbidden transitions in spectra of highly ionized atoms, particularly Fe. The ionization potentials involved are as high as several hundred volts, indicating a kinetic temperature of the order of 10^6 degrees K in the corona. Alfven[11] proposed a corona consisting entirely of ions and electrons having thermal energies corresponding to this high temperature. The highly stripped atoms emit soft x-rays in recombining with electrons, the energy of the x-ray quantum being roughly equal to the potential energy of the ion resulting from the recombination. From considerations of the lifetimes of ionized states of Fe atoms in the corona. Alfven concluded that the maximum ionization potential reached was about 900 ev. Hoyle[12] derived the shape of an x-ray spectrum, assuming it due entirely to iron, which consisted of a slowly rising intensity approximately proportional to the quantum energy up to about 500 ev beyond which the intensity fell rapidly as the inverse 5th power of the quantum energy. The absorption characteristic of this latter spectrum of x-rays is included in the illustration of Fig. 6. It differs only slightly from the corresponding absorption curve of blackbody radiation at 10^6 °K, being shifted upward about 3 kilometers with respect to the blackbody curve.

The present experimental measurement of solar x-rays follows earlier detections made by NRL investigators with the aid of photographic film packets[13] and with thermoluminescent powders.[14,15] To check further the hypothesis that x-rays from the corona are responsible for E-layer will require that the x-ray measurements be extended to longer wavelengths, preferably up to 100A. In preparation for V-2 #49, several tubes with very thin aluminum coated nitroceullulose windows were constructed in addition to those with Be windows. Unfortunately, however, those tubes leaked sufficiently during the long interval between filling at NRL and firing at White Sands, to make them unusable in the experiment. To overcome the problem of deterioration, a free-flow counter technique was adopted for an experiment attempted in January, 1951. That experiment was unsuccessful because the rocket engine failed. Another attempt is scheduled for June, 1951, in a V-2 rocket which wlli carry photon counters capable of covering the x-ray region up to at least 50A.

The authors are grateful to Dr. E. O. Hulburt for many discussions of the experiment and to Dr. R. Tousey, Dr. K. Watanabe, and Mr. F. S. Johnson of the Optics Division for their valuable advice and assistance in connection with the ultraviolet spectral sensitivity measurements. The execution of the rocket experiment was possible only with the generous assistance of Dr. Newell and other members of the Rocket Sonde Branch.

[8] E. O. Hulburt, Phys. Rev. **53**, 344 (1938).
[9] D. R. Bates and F. Hoyle, Terr. Mag. Atmos. Elect. **53**, 51 (1948).
[10] B. Edlén, Z. Astrophys. **22**, 30 (1942) and Monthly Notices Roy. Astron. Soc. **105**, 323 (1945).
[11] H. Alfven, Arkiv. Mat. Astron. Fysik. **27A**, 25, (1941).
[12] F. Hoyle, *Some Rrecent Researches in Solar Physics* (Cambridge University Press, Cambridge, Massachusetts, 1949).
[13] T. R. Burnight, Phys. Rev. **76**, 165 (1949).
[14] Purcell, Tousey, and Watanabe, Phys. Rev. **76**, 165 (1949); Watanabe, Purcell, and Tousey, NRL Report No. 3733 (1950).
[15] Tousey, Watanabe, and Purcell, Phys. Rev. **83**, 792 (1951).