

THE SPECTRAL DISTRIBUTION OF ULTRAVIOLET
LIGHT OBTAINED FROM PROBES

by

R. Tousey
U. S. Naval Research Laboratory
Washington 25, D. C.

* * *

INTRODUCTION

The radiation from the sun is perhaps the most important environmental factor affecting operations in space. In order to be prepared to solve all the problems of space flight it is necessary to have a detailed knowledge of the intensity distribution within the spectrum, and of the variations that may occur in the spectrum from time to time. Although the sun is the source of both particle and optical radiations, only the latter are considered in this paper.

The study of the solar spectrum throughout the visible and much of the infrared and ultraviolet can best be conducted from the earth's surface. Only for the measurement of wavelengths below about 2900 A is it necessary to resort to rocket and satellite experimentation.

Contrails

Commencing early in 1946 the U. S. Naval Research Laboratory (NRL) has been engaged in the measurement of the solar spectrum, from the ultraviolet through the vacuum region and into soft and even rather hard x-rays. A similar program, conducted by the Geophysics Research Directorate (GRD) of the Air Force Cambridge Research Laboratories, has resulted in data which complement the results of NRL. As a result, the solar spectrum as it impinges on the outermost atmosphere of the earth is now fairly well mapped. There are a great many matters left to be explored, but the first approximation is in hand.

It is now well established that different places on the sun radiate unequally. This has long been known in the visible and near ultraviolet, but there the effect is very small. In the rocket ultraviolet and x-ray regions, however, the emission comes more and more from hot spots on the sun. This is known from the photograph of the sun obtained with the Lyman-alpha line of hydrogen, by Purcell, Packer, and Tousey,¹ and from the solar photograph made with 20-60 A x-rays by Blake, Unzicker, and Friedman.²

For environmental calculations, however, the radiation from the entire solar disc is the quantity to be considered; the irregular nature of the emission is of interest, principally, because it reflects the fact that the emission from the sun changes from time to time, as the sun's rotation brings new regions into view, and as the activity

changes during the sunspot cycle.

THE NEAR ULTRAVIOLET

The spectral intensity distribution is known with high resolution and reasonably good accuracy from the visible to about 2000 A. New measurements by Dunkelman and Scolnik³ of the difficult region 4000 to 3000 A were obtained from Mount Lemmon, Arizona. These are the most accurate available. The absolute energy scale for this part of the spectrum was set by Johnson⁴ from a reconsideration of the long program of measurements conducted by the Smithsonian Institution, and the infrared and ultraviolet corrections. Johnson's value of the solar constant is 2.00 ± 0.04 calories/cm²min. The Mount Lemmon data, and the rocket spectra to 2000 A are adjusted to be consistent with this value.

The NRL rocket spectrum has been published by Wilson et al⁵ for the wavelength range 2990 to 2635 A; the region 2635 to 2085 A is covered by Malitson et al.⁶ Curves are presented at a resolution of about 0.5 A, on an absolute energy scale tied to the Mt. Lemmon curve.

For many purposes data with less spectral resolution are more convenient. For this reason a table was published by Johnson,⁴ covering the spectral range to 2200 A in steps of 50 A. This table is based on the early NRL rocket data and is essentially correct to about 2400 A; below 2400 A the data are low, by a factor which reaches about 2 at 2200 A.

THE EXTREME ULTRAVIOLET

The region from 2000 to 500 A has been studied by NRL using normal incidence grating spectrographs and photographic recording. On April 19, 1960, the latest in a long series of flights, a new type of spectrograph was employed. The background of instrumental stray light, so long the factor which limited the accuracy of the results, was eliminated by the use of double dispersion. In Figs. 1 and 2 are shown two portions of the spectrum. Everything recorded was real solar emission at the wavelengths shown.

The new spectrum shows that throughout this region the sun radiates a continuous spectrum, with emission lines superimposed upon it. This is unlike the visible and near ultraviolet, where the continuum is covered with absorption lines. The extreme ultraviolet originates from higher levels in the sun's atmosphere than does the near ultraviolet and visible. The extreme ultraviolet continuum probably comes mainly from the very low chromosphere. The emission lines are emitted from all regions from the low chromosphere to the corona, depending on the particular line. For example, the many lines of neutral Carbon (C I) must come from low in the solar atmosphere; on the other hand, the resonance lines of seven times ionized Neon (Ne VIII) at 770, 780 A, must be emitted from the corona only, since a temperature of the order of one million degrees is required to produce

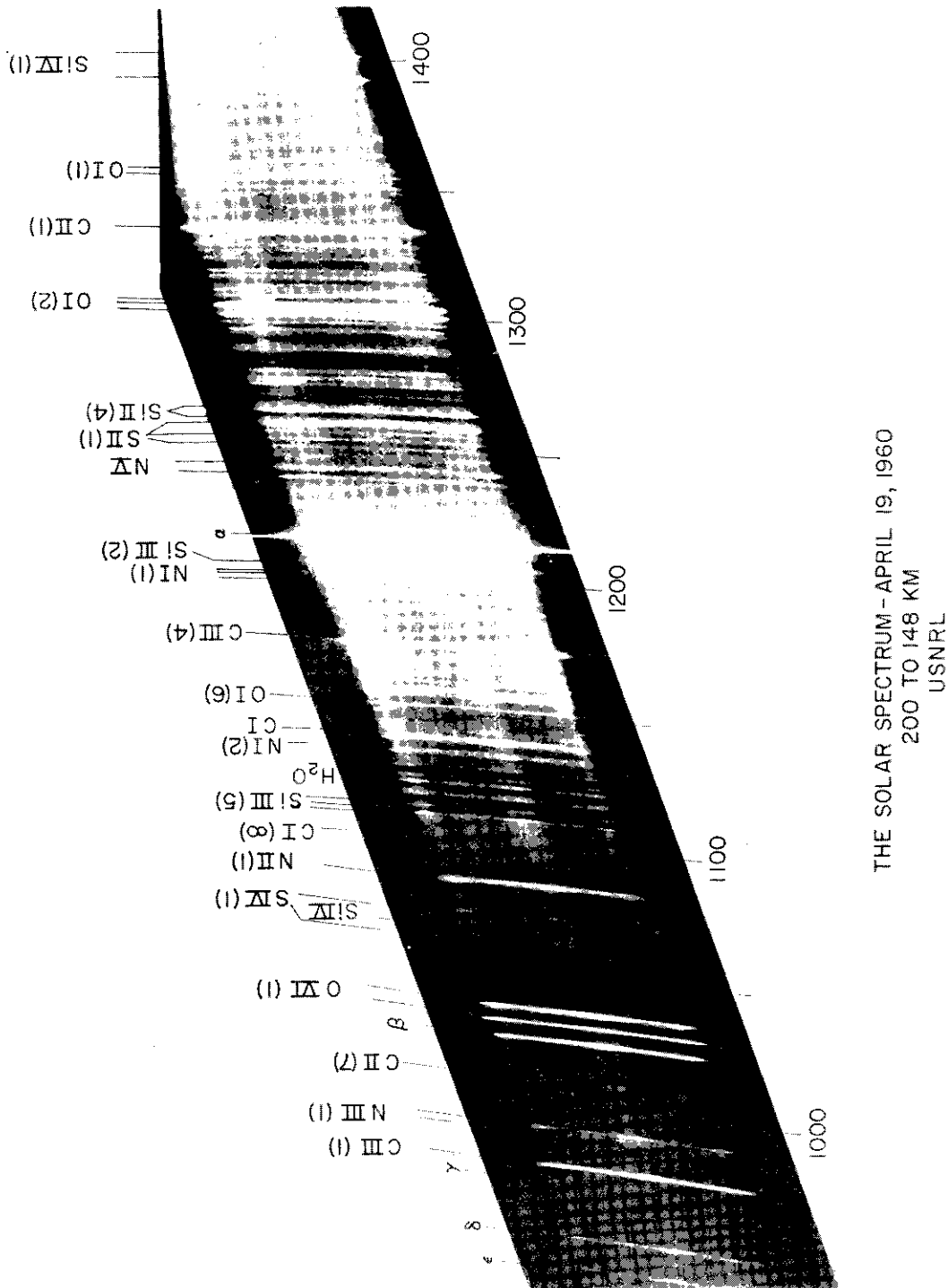


Figure 1 The Solar Spectrum Photographed at an Altitude of 149 to 200 km on April 19, 1960. The Double-Dispersing Spectrograph and DC-3 Film were used with an Exposure Time of 60 sec.

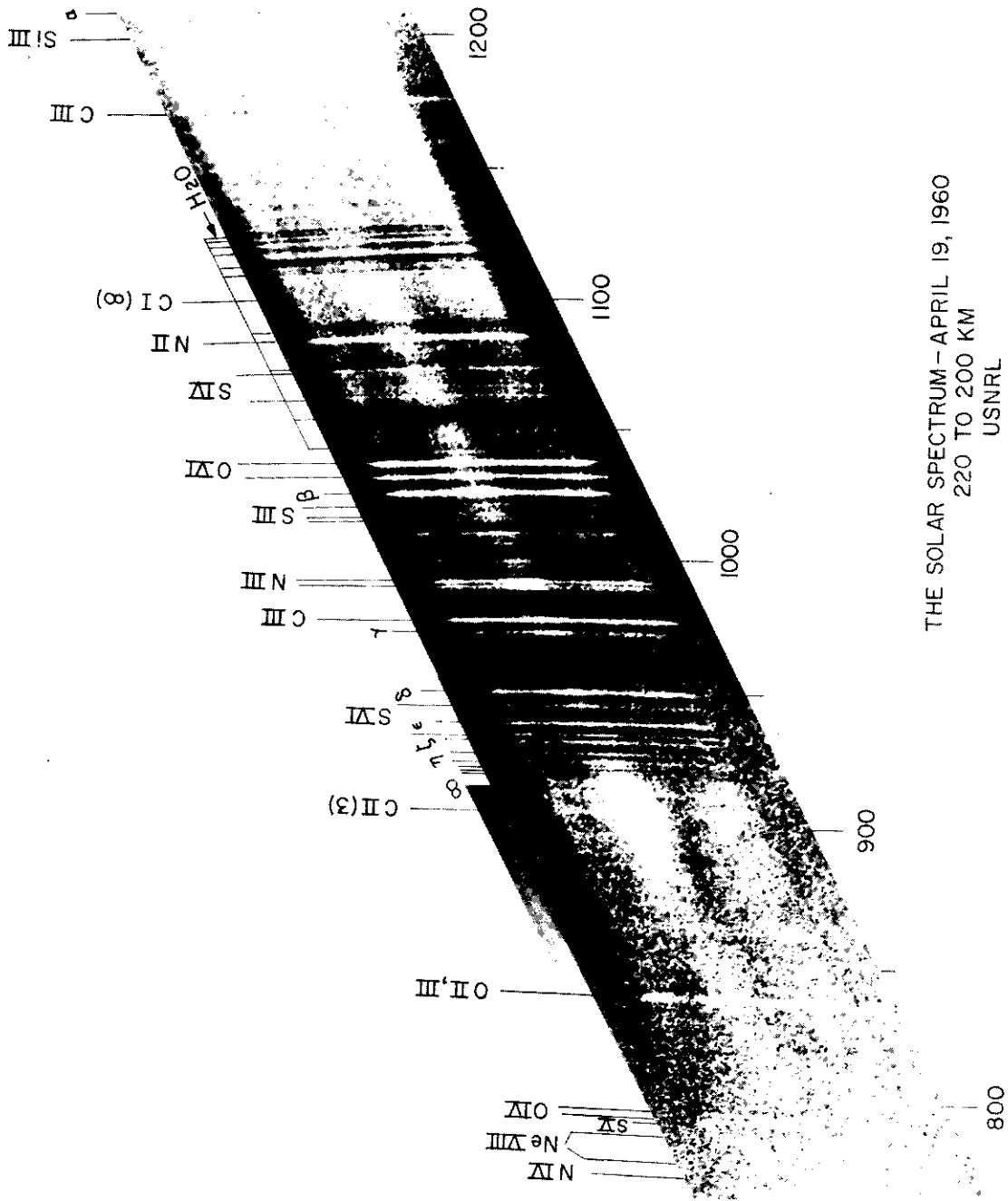


Figure 2 The Solar Spectrum in the Region of the Lyman Series of Hydrogen, Photographed at an Altitude of 200 to 220 km on April 19, 1960. The exposure time was 60 sec and SC-4 Film was employed in the Double-Dispersing Spectrograph.

Contrails

such a high state of ionization.

A most significant feature is the emission from hydrogen, which is very strong. The Lyman series has its first line, Lyman-alpha, at 1216 A. This carries about $6 \text{ ergs/cm}^2 \text{ sec}$ to the earth during times near sunspot maximum; the radiation may be considerably less at sunspot minimum. The higher members of the series are indicated in Fig. 2 and shown followed by the Lyman continuum.

Similar work by Hinteregger⁷ of the GRD, has been performed with a completely different technique. Grazing incidence monochromators with photoelectric scanning are flown. This instrument gives data to shorter wavelengths, because of the use of grazing incidence and the high reflectance values associated with it. However, the spectral resolution is much lower.

The best spectral intensity data from 2000 to 800 A, resulting from the most recent work of both NRL and GRD, are shown in Fig. 3. The NRL data were actually obtained at much greater resolution, and then averaged over a 10 A span to make comparison with the GRD data possible. The vertical scale gives the energy incident per $\text{cm}^2 \text{ sec}$ in a 10 A wide wavelength interval.

The solar spectrum follows a 5000° to 4700°K black body curve from 2085 A to about 1300 A, with certain emission lines superimposed. Then the continuum rises toward Lyman-alpha, and falls again on the short-wavelength side;

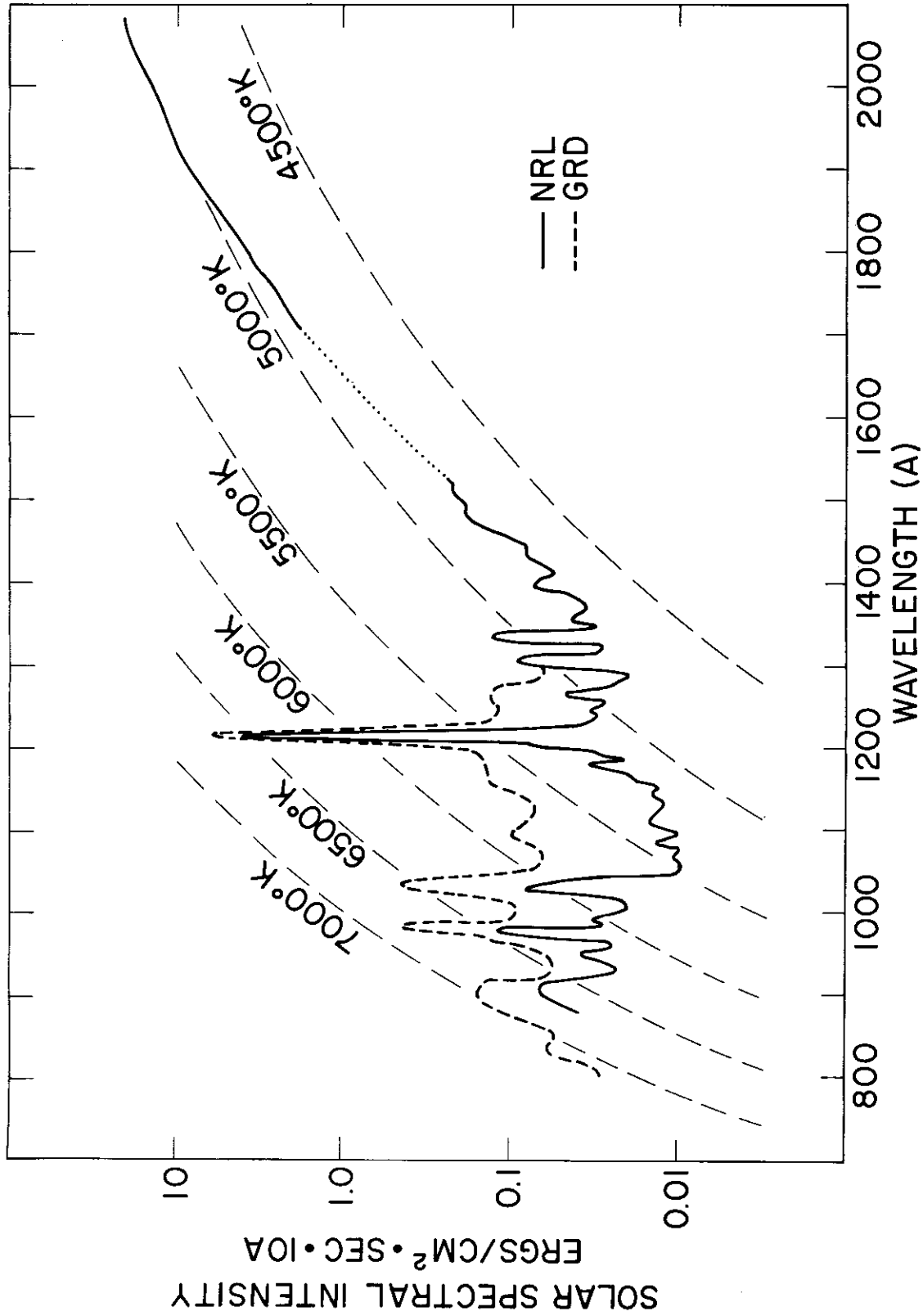


Figure 3 The Radiation from the Entire Sun in the Extremes Ultraviolet to 800 A. Curves are shown from the Work of Detwiler, Purcell, and Tousey of NRL, and Hinteregger of the GRD.

Contrails

relative to a black body, it builds up, however, reaching the 6750°K level in the Lyman continuum below 912 A. This reflects the fact that the emission originates higher in the solar atmosphere, where the temperature is increasing outward.

The NRL curve of Fig. 3 is lower by a factor of about 2 than the curve reproduced in the preprint of this report. The earlier curve may be considered an upper limit, based on the assumption that water vapor, whose absorption features were identified in the spectrum, surrounded the rocket in the form of an enveloping cloud produced by the process of desorption. It now appears more likely that most of the water vapor was within the instrument, and the curve of Fig. 3 was lowered to conform to this assumption. In either case the NRL curve is somewhat lower than that obtained by GRD from their January 1960 flight.

From 800 to 60 A preliminary data are available from Hinteregger⁷. These show that there is intense emission at 584 A and 304 A from neutral and ionized helium. The two lines produce of the order of $0.5 \text{ erg/cm}^2\text{sec}$ at the earth. Also present are certain other lines and a rather intense background, that must consist largely of unresolved lines. Some continuum radiation is also present, for example the He II continuum below 226 A.

Within the x-ray region data are available from NRL. Figure 4 is a summary of the results obtained by Friedman,

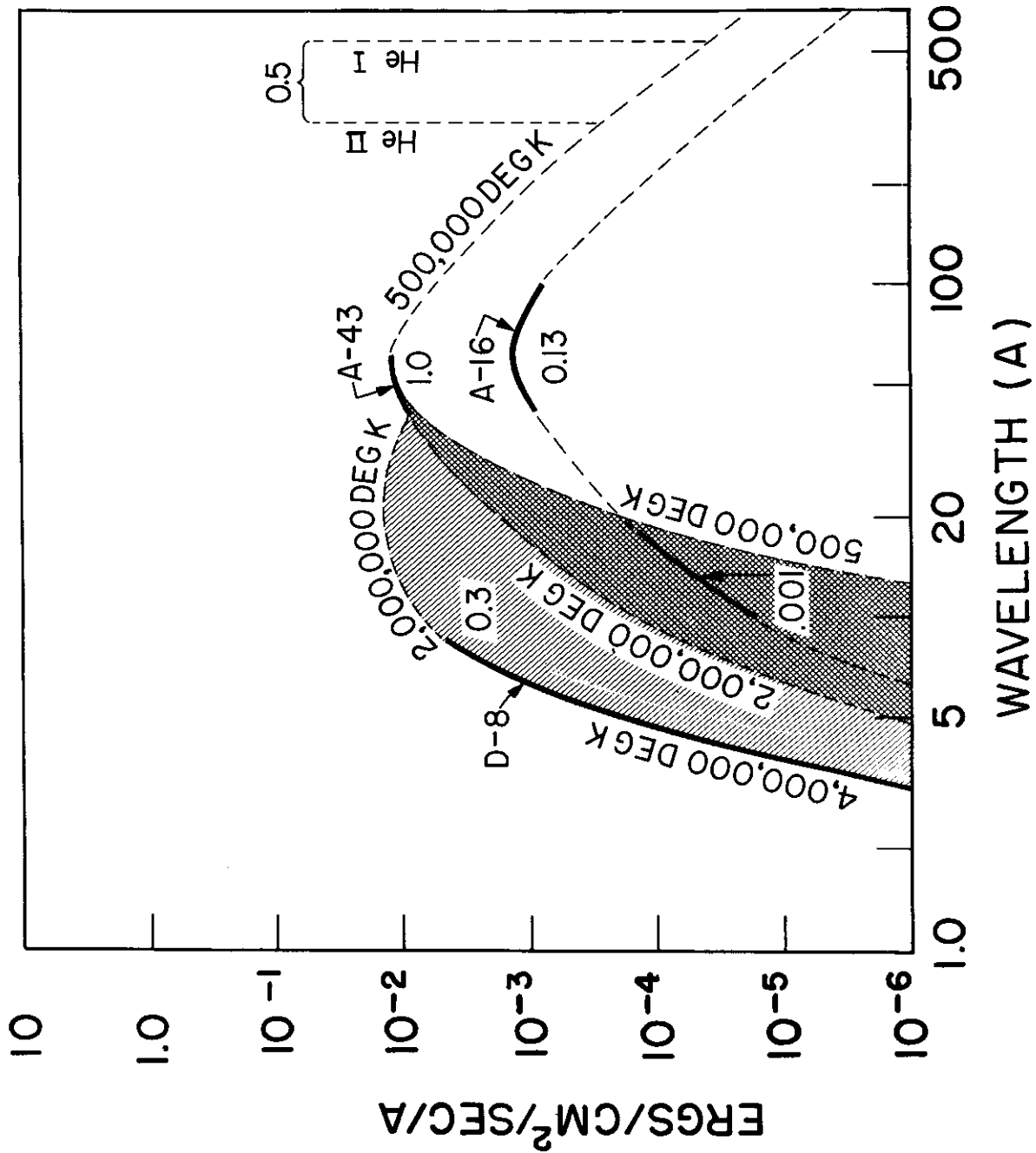


Figure 4 The Solar X-ray Spectrum

Contrails

Chubb and their associates.⁸ The measurements were made using photon counters of known spectral response; additional spectral information was obtained by studying the rate of attenuation of the signals with altitude, using the atmosphere itself as a spectral analyzer.

The quiet sun, during periods near sunspot maximum emits an x-ray flux roughly as shown in Fig. 4, such that the total emission is about $1 \text{ erg/cm}^2 \text{ sec}$. The broad features of this emission can be approximated by a superposition of gray body emission curves. The bulk of the x-ray energy is emitted in the longer wavelengths, i.e 20 to 100 A, and this emission can be conveniently described by a $500,000^\circ\text{K}$ gray body curve. In addition, there is a short wavelength tail which follows an approximately $2,000,000^\circ\text{K}$ curve. The x-ray photograph of the sun,² obtained with a pin-hole camera, shows that the x-rays originate largely in coronal condensations associated with active regions on the sun. During non-flare periods, x-ray emission is negligible below 5 A. Also the total x-ray flux shows large variations with the solar cycle, the total emission varying by a factor of 5 between solar minimum and solar maximum. The variation in x-ray intensity increases toward shorter wavelengths, so that x-rays of less than 15 A show a solar cycle variation of a factor of 30.

Contrails

The changes in radiation during solar flares have been the object of much study by Chubb and Kreplin⁸ at NRL. Rockets have been launched during flares, to observe the changes in radiation. More recently, Satellite 1960 η 2 launched on June 22, 1960, contained x-ray and Lyman-alpha solar monitors.⁹ Data now being reduced from 1960 η 2 confirm the earlier rocket results, which showed that the short wavelength x-ray intensity increases greatly during flares. The Lyman-alpha line, however, is not noticeably affected.

Figure 4 shows a curve obtained during a small flare (Class I). The intensity below 20 A increased, and radiation was detected to about 3 A. During intense flares, however, the change is much greater. Hard x-rays of wavelengths as short as 0.1 A were detected during one Class II+ flare on September 1, 1959. This very high energy emission is again a tail on the x-ray spectrum emitted by the flare and contains only a small portion of the total flare emission.

The attenuation of these radiations by the earth's atmosphere is a study in itself. Most of the radiation suffers little absorption above 200 km, and the x-ray end and Lyman-alpha penetrate far below 100 km. However, certain wavelengths are absorbed at very high altitudes indeed. Perhaps the highest is the very center of the Lyman-alpha line. The high resolution spectrum of this

Contrails

line, obtained by Purcell and Tousey,¹⁰ shows an absorption core produced by neutral hydrogen in the exosphere, at a temperature of 1000° to 2000°K ; some of the hydrogen may also be in interplanetary space.

The possibility of absorption by gases carried with vehicles should not be overlooked. For example, in Fig. 2 there can be seen strong absorption bands produced by water vapor. This is water carried with the rocket. Thus vapors released from the vehicle may have an important screening action. In all probability a considerable time in orbit would be required before a large vehicle would be completely outgassed.

SUMMARY

The intensity distribution in the short-wavelength end of the solar spectrum, as it traverses free space at the distance of the earth, is summarized in the following table, which is presented only as a rough guide:

TABLE I

λ (A)	Fraction of total solar energy below λ
7000	0.5
4000	0.1
3000	0.01
2400	0.001
1900	0.0001
1600	0.00001
1000	0.000001

REFERENCES

1. Purcell, J. D., Packer, D. M., and Tousey, R., Nature 184, 8, 1959.
2. Blake, R. L., Unzicker, A. E., and Friedman, H., Report of NRL Progress June 1960, p. 14; Chubb, T. A., Friedman, H., Kreplin, R. W., Blake, R. L., and Unzicker, A. E., to be published in the Proceedings of the Tenth International Astrophysical Symposium, Liege, 1960.
3. Dunkelmann, L. and Scolnik, R., J. Opt. Soc. Am. 49, No. 4, pp 356-367, Apr 1959.
4. Johnson, F. S., J. Meteorol. 11, pp 431-439, 1954.
5. Wilson, N. L. Tousey, R., Purcell, J. D., Johnson, F. W., and Moore, C. E., Astrophys. J. 119, No. 3, May 1954.

Contrails

6. Malitson, H. H., Purcell, J. D., Tousey, R., and Moore, C. E., *Astrophys. J.*, Nov. 1960.
7. Hinteregger, H. E., GRD, AFCRL, Bedford, Mass. Private communication.
8. See, for example, *Physics of the Upper Atmosphere*, Ed. J. A. Ratcliffe, Published by Academic Press, New York-London, 1960, pp 133-215, Chapter 4, "The Sun's Ionizing Radiations," by H. Friedman.
9. Kreplin, R. W., Chubb, T. A., and Friedman, H. Report of NRL Progress, July 1960, p 1, and *Naval Research Reviews*, Nov. 1960, p 22.
10. Purcell, J. D., and Tousey, R., *J. Geophys. Res.* 65, 370, 1960.

LIST OF FIGURES

- Fig. 1. The solar spectrum photographed at an altitude of 149 to 200 km on April 19, 1960. The double-dispersing spectrograph and DC-3 film were used with an exposure time of 60 sec.
- Fig. 2. The solar spectrum in the region of the Lyman series of hydrogen, photographed at an altitude of 200 to 220 km on April 19, 1960. The exposure time was 60 sec and SC-4 film was employed in the double-dispersing spectrograph.
- Fig. 3. The radiation from the entire sun in the extreme ultraviolet to 800 A. Curves are shown from the work of Detwiler, Purcell, and Tousey of NRL, and Hinteregger of the GRD.
- Fig. 4. The solar x-ray spectrum.