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MEASURES OF THE SOLAR SPECTRAL IRRADIANCE BETWEEN 1200 AND 3000Å

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1. INTRODUCTION

The solar flux emitted in the wavelength region from 1200 to 3000 Å is of great interest to both solar and atmospheric physicists. In the visible and infrared, the solar spectrum is essentially a continuum, however, absorption lines superimposed upon the continuum become increasingly more pronounced as one goes to shorter wavelengths in the near ultraviolet near 3000 Å. Continuing to still shorter wavelengths, a very steep decrease is observed in the continuum flux associated with the Al I ionization edge and its associated continuum at shorter wavelengths. Similar ionization edges with their associated continuua are observed for H, M_g, Si, Fe, and C. These elements represent the principal sources of solar opacity in the wavelength region from 1200 to 3000 Å. From 3000 Å to 2100 Å the absorption lines superimposed in the continuum absorb increasingly more energy. As one moves further into the ultraviolet past the Al I ionization edge, the importance of emission lines increases rapidly with the absorption lines disappearing near 1500 Å. For wavelengths shorter than 1400 Å, the chromospheric and coronal emission lines begin to dominate the emission in the continuum.

The source of the solar continuum radiation changes from the photosphere to the chromosphere as the wavelength of the solar spectrum decreases from 3000 to 1200 Å. In passing through this transition region, the brightness temperature of the solar continuum goes through a minimum between 1500 to 1800 Å. The increase in the absorption cross-sections with decreasing wavelengths causes the effective emitting height of the solar continuum to move upwards in the solar atmosphere. These effects are shown in Figure 1 (Vernazza et al., 1976). The shaded band represents the brightness temperature T_b (legend on the right) of the continuum at the center of the solar disk. The solid line gives the height h (legend on the right) in the solar atmosphere at which the solar spectral flux has an attenuation of 1/e (or has an optical depth τ_λ equal to one). The height is measured from the level where τ_λ is 1 for λ = 5000Å. The value of τ_b is from observations and that of h from the solar model computations of Vernazza et al. (1976).

In the terrestrial atmosphere, solar radiation from 1250 to 2000Å is absorbed in the lower thermosphere and mesosphere by O_2 which produces atomic oxygen through the dissociation of O_2. The longer wavelengths from 2000 to 3000 Å are absorbed in the upper and lower stratosphere. This radiation is responsible for the photochemistry of stratospheric ozone. At the long wavelength end the absorption cut-off for solar flux which reaches the ground is strongly dependent upon the total ozone column amount which is highly variable with season and geographical location. Figure 2 gives an approximate representation of the absorption of normally incident solar spectral flux in the Earth's atmosphere as a function of wavelength (Friedman, 1960). The y-axis gives the altitude above sea-level at which solar flux is reduced to 1/e of the extra-terrestrial value.

Thermal gradients, which are variable with altitude, geographical location, season and solar flux represent a major driving term in the circulation of the stratosphere. Investigations of atmospheric phenomena on synoptic and climatological time scales can serve as a useful indicator for the behavior of the Sun as an ultraviolet variable star. The variability of the Sun below 1200Å is well established not only from direct observations of the Sun, but also from in-situ measurements of atmospheric constituents and parameters and satellite drag effects. The problem of determining the temporal behavior of the solar flux in the region from 1200 to 3000Å is much more difficult since the magnitude of the variability is less than in the EUV, and satellites cannot operate in the region of the atmosphere bounded by the lower thermosphere below 120 km and the stratosphere.

In this region, only remote atmospheric sounding techniques are possible and when coupled with the fact that dynamics play important roles in atmospheric structure and composition, it becomes quite difficult to separate out effects which can be attributed to the intrinsic variability of the Sun.

2. SOLAR SPECTRAL IRRADIANCE

Measurement of the solar spectral energy distribution is usually in terms of either the spectral radiance at the center of the solar disk (units, ergs s^{-1} cm^{-2} nm^{-1} $ster^{-1}$) or the spectral irradiance due to the whole Sun at one A.U. Because of limb darkening (or brightening at short wavelengths) and increased brightening in active regions, the radiance is not uniform at all points on the disk. The relation between average spectral radiance of the disk, L_λ, and that at the disk center, L_{λ_c}, is:

$$L_\lambda = L_{\lambda_c} \int_0^{\pi/2} R_{\lambda\theta} \cos\theta \sin\theta \, d\theta \tag{1}$$

where θ is the angle subtended at the center of the Sun by two solar radii, one passing through the disk center and the other passing through any other surface element on the Sun, and $R_{\lambda\theta}$ is the limb darkening (or brightening) function, namely, the ratio of radiance of a surface element at angle θ to the radiance of the disk center at wavelength λ. To the extent that L_{λ_c} and $R_{\lambda\theta}$ are known, L_λ can be evaluated.

Spectral irradiance of the Sun at one A.U. is:

$$\begin{aligned} E_\lambda &= 2\pi \, (r^2/R^2) \, L_\lambda \int_0^{\pi/2} \sin\theta \cos\theta \, d\theta \\ &= \pi \, (r^2/R^2) \, L_\lambda = 6.7997 \times 10^{-5} \, L_\lambda, \end{aligned} \tag{2}$$

where r is the solar radius and R is one A.U.

Total irradiance or the solar constant is:

$$E = \int_0^\infty E_\lambda d_\lambda. \tag{3}$$

A particular type of solar observation, i.e., solar spectral irradiance or radiance, is usually determined by the nature of the scientific investigation. In general, measurements of the solar spectral energy distribution are of irradiance or radiance, respectively, according as the investigations are for terrestrial or solar phenomena. Since measurements of the solar spectral energy distribution from 1200 to 3000Å must be made from altitudes where the effects of atmospheric attenuation are negligible, experimentally it is easier to measure irradiance since telescope systems with high pointing accuracy are not required for such measurements.

A separate topic, which will not be discussed in this work due to limitations of space but which obviously is of great importance, is the question of instrument calibration techniques.

Basically, there are two ways in which the problem can be approached. One can either measure the wavelength dependence of the instrument transfer function and detector efficiency or illuminate the instrument with standards of spectral radiance or irradiance. When using the latter technique, it is important that the spectral energy distribution of the radiation standard and of the Sun not be too dissimilar over the spectral bandpass of the instrument.

Conversion of measurements of the central disk solar spectral radiance to irradiance for the region of 1200 to 3000Å is complicated because the character of the solar spectrum changes from line absorption to line emission and from limb darkening to limb brightening as one proceeds to shorter wavelengths. In addition, the limb function not only varies with wavelength, but is also a parameter of each individual spectral line. This problem has been discussed in great detail by Vernazza et al. (1976).

Table I gives a list of the major sources of data on solar spectral irradiance of the Sun. This is not a fully exhaustive list, and the information about type of measurement and method of calibration is necessarily very brief. The authors and the references are given in the first column, and the dates on which the measurements were made in the next column. The listing is in the order of these dates.

The values of solar spectral irradiance from eight different sources are given in Table II. The wavelength range for the table is 1000 to 3000Å though not all of the measurements cover the full range. The units of irradiance are ergs sec^{-1} cm^{-2} per 10Å bandwidth (or W m^{-2} μm^{-1}) except f r the last column which is in units of 10^{10} photons cm^{-2} sec^{-1} nm^{-1}. The sources for these data are: Col. 3, Donnelly and Pope (1973); Col. 4, Heroux and Swirbalus (1976); Col. 5, D. Samain and P. C. Simon (1976) and A. L. Broadfoot (1972); Col. 6, Detwiler et al. (1961); Col. 7, M. P. Thekaekara (1974); Col. 8, Brueckner et al. (1976); Cols. 9 and 10, G. J. Rottman (1974) data from December 13, 1972 and August 30, 1973, respectively; and Col. 11, Donnelly and Pope (1973). The entries in columns 3 and 11 are equivalent and are the only ones which cover the full range from 1000 to 3000Å and with 10Å resolution. They are taken from a detailed NOAA Technical Report which presents the solar flux in the wavelength range 1 to 3000Å for a moderate level of solar activity (10.7 cm radio flux = 150 x 10^{22} W m^{-2} Hz^{-1} at 1 A.U.). The report does not present new measurements but gives a critical evaluation of all previous measurements made from balloons, rockets and satellites. The major sources of data for the wavelength range 1000 to 3000Å are Hinteregger (1970), Timothy et al. (1972), Vidal-Madjar et al. (1973), Rottman (1973), Dupree and Reeves (1971), Detwiler et al. (1961), Prag and Morse (1970), Parkinson and Reeves (1969), Widing et al. (1970), Carver et al. (1972) and Broadfoot (1972). Two of these data sets, those of Broadfoot and Detwiler et al., are listed separately in colums 5 and 6 respectively, of Table II. There are several emission lines below 1560Å. Donnelly and Pope list 20 of these single lines or groups of lines. In Table II the energies of these lines have been added to that of the continuum in the corresponding 10Å range. The strongest of these is Lyman α at 1215.7Å with an energy flux according to Donnelly and Pope of 5.1 erg s^{-1} cm^{-2}, which is nearly twice the total solar irradiance below this wavelength.

In column 4 the values of spectral irradiance obtained by Heroux and Swirbalus (1976) from a rocket flight of November 2, 1973 are presented. The authors also made a later flight on April 23, 1974 and values from the second flight are shown graphically but not listed in tabular form in their publication. The second set of values were 5 to 10% lower than the first, a difference which is attributed to a change in spectrometer efficiency, not to a decrease in solar flux. Unlike the other entries in Table II, these values have not been adjusted to 1 A.U. Since the Sun-Earth distance on November 2 was 0.8% less than 1 A.U., the values of column 4 should be adjusted downwards by 1.6%. The wavelength range for these measurements is 1230 to 1940Å.

In column 5 the values are from two sources. For the range 1510 to 2090Å the data are from a preprint of Samain and Simon (1976), based on a rocket-borne spectrograph flown on April 17, 1973. Direct measurements over another part of the spectrum, 2105 to 3005Å, are quoted from A. L. Broadfoot in the same column. For Broadfoot's data and for the next two columns, the entries fall midway between the lines of the other columns, since the measurements published in the literature apply to bands centered at integral multiples of 10Å. Thus, for example, the first entry in column 5 for 2100 to 2110Å is 39.4 which is the average irradiance in the range 2105 to 2115Å. The values listed here were derived by converting Broadfoot's photon flux data into ergs, and further increasing them by 3.18% to adjust to 1 A.U.

The data in column six are from rocket flights of a much earlier period made by the group at the Naval Research Laboratory. The measurements were on a relative scale, and conversion to absolute units was made by comparing the results in the range beyond 3000Å with the data obtained by Dunkelman and Scolnik (1959) from Mt. Lemmon, and scale adjustments of these data made by Johnson (1954) on the solar spectrum. The values are averages over 50Å bandwidths.

In column 7 a similar set of values averaged over wide wavelength bands derived by M. P. Thekaekara (1973, 1974) are given. These values are from the first portion of Thekaekara's table which extends from 1150Å to 1000 μm. The direct measurements of the GSFC group from the Convair 990 research aircraft (Thekaekara et al., 1969) cover the wavelength range 3000Å to 15 μm. The extension of the results to wavelengths below 3000Å was based on the results of Heath (1969), Detwiler et al. (1961) and Parkinson and Reeves (1969), with adjustments in the scale based on the absolute measurements of the GSFC group beyond 3000Å from Convair 990.

Data over a more limited wavelength range, 1740 to 2105Å are given in column 8. They are from a preprint of Brueckner et al. (1976) and were obtained on a rocket flight of September 4, 1973. Data were also obtained on this flight for the lower wavelength range, down to 1175Å, but have not yet been published. The measurements were made with a spectrometer pointed at a 60 x 60 arc seconds area of the quiet Sun. The authors give four sets of data for (1) plage, Sun center, (2) quiet Sun, Sun center, (3) quiet Sun, average disk intensity and (4) quiet Sun flux at 1 A.U. The fourth set of values is quoted here. Brueckner's listing is for 5Å averages and pairs of values have been summed to give irradiance over 10Å bandwidths.

Two sets of values obtained by G. J. Rottman (1974) from rocket flights of December 13, 1972 and August 30, 1973, respectively are given in columns 9 and 10. The wavelength range is 1160 to 1800Å.

The final column, as stated earlier, is the solar flux in units of 10^{10} photons $cm^{-2}\ s^{-1}\ nm^{-1}$, the values are from Donnelly and Pope.

Most of these data sets are also shown graphically in Figures 3 and 4 for wavelength ranges 1300 to 2300Å and 2000 to 3000Å respectively. Data not included in these figures are those of Detwiler et al. which are significantly different from all later measurements and the data from Rottman's second flight which are too close to those of the first flight. Three other sets of data are also shown graphically. They could not conveniently be entered on Table II since the wavelength intervals are not multiples of 10Å. They are from Ackerman (1971), Simon (1975) and Heath (1973). Ackerman's listing is based on a review of several earlier measurements and covers the whole wavelength range of these figures. Simon's data were obtained from balloon measurements, extrapolated to zero air mass. They cover the wavelength range 1961 to 2299Å and 2857 to 3525Å. Heath lists solar irradiance at 12 wavelengths between 2557 and 3399Å. The measurements were made from Nimbus 4 spacecraft with a double grating monochromator which had a 10Å spectral bandpass and a triangular slit function.

The results presented in Table II and Figures 3 and 4 fail to show the fine structure which exists in the solar spectrum. Many of the observers obtained spectra with considerably higher resolution than the 10Å bandwidth adopted for these figures. Figure 5 from Broadfoot (1972) gives an example of the high resolution spectra available in literature. Broadfoot also gives an extended table of irradiance values at 1Å intervals and includes with his spectral curve, a comparison spectrum based on earlier data of the Naval Research Laboratory. These data are not reproduced here. The line structure of Broadfoot's spectra is essentially the same as that of the earlier NRL spectra but the flux values are lower. The maximum differences between the two sets of data are about 30% at 2500Å and 40% 3200Å when the ratio curve is smeared with a triangular function of 25Å half-width. Without such smearing, the differences are greater. These differences, for example, by a factor of 2 at 3160Å, should be attributed to measurement problems rather than to intrinsic variations in solar output.

Digitized versions of high resolution spectra are available in two major reports. A NASA Report prepared at J.P.L. by Brinkman et al. (1966) gives in digital form the densitometer tracings of the NRL spectra. The region covered is 880 to 1550Å and 1760 to 2990Å. The tables give the irradiance at intervals of 0.1Å and 0.2Å and also integrated values of the irradiance over intervals of 1, 10 and 50Å. An NCAR report published by Furukawa et al. (1967) gave a new estimate of the absolute solar flux of the digital data of Brinkman et al., using unpublished NRL spectra, Soviet data, and ground based measurements. The wavelength range is 2080 to 3600Å, with over 2400 data points for the range 2080 to 3050Å and about 10,000 data points for the range 3050 to 3600Å.

A major problem with all measurements of spectral radiance or irradiance is the absolute radiometric accuracy. Tungsten coiled coil lamps referred to as quartz-iodine lamps (1000 W) are available from NBS and many commercial suppliers, as standards of spectral irradiance. They cover the range 2500 to 25000Å. Such lamps have been issued since 1964 (Stair et al., 1963) by the NBS, but since 1967, doubts have been raised as to their absolute accuracy. As a result of more recent research conducted at NBS, new spectral irradiance standards became available in 1973. A comparison of the scales of 1964 and 1973 shows that in the wavelength range between 2500 and 3000Å the new scale is lower by percentages varying between 5 and 10 percent. The uncertainties in other sources and in the detectors used below 2500Å are somewhat greater. With possible inaccuracies in the so-called "standards," the absolute accuracy of the transfer in calibration to an experiment on rocket, balloon or spacecraft decreases. Hence, it is not surprising that measurements of the Sun made by different observers do not yield identical values. As an example of the variant readings, the data from six different measurements are shown in Figure 6 which is reproduced from Figure 8 of Donnelly and Pope (1973). The wavelength range, 1400 to 1750Å, is a third of that covered in Figure 3 and the irradiance scale is more expanded. Over most of the range, the data of Widing et al. (1970) are about three times greater than those of Parkinson and Reeves (1969) and at 1600Å the former is 5.2 times the latter. The brightness temperature which best fits the data is 4700 K for Widing et al. and 4400 K for Parkinson and Reeves. The ratio of solar irradiances at these two temperatures decreases gradually from 4.44 at 1400Å to 3.30 at 1750Å.

3. SOLAR FLUX VARIABILITY

The effects of solar variability on the density of the thermosphere are well established from satellite drag measurements (King-Hele and Quinn, 1967) for sunspot maximum and sunspot minimum and (Jacchia, L., 1963) for the 27-day solar rotational period. The principal region of the solar flux which produces this effect originates below 1200Å. Direct measurements of the variability associated with the 27-day solar rotational period of the solar EUV flux below 1200Å have been reported by numerous authors, e.g., Hall and Hinteregger (1970). The magnitude of the variability of the solar EUV flux below 1200Å between solar minimum and solar maximum, however, has not been measured directly.

Above 1200Å, the 27-day variability in the UV flux has been measured from satellites over extended periods by Vidal-Madjar et al. (1973) at L_α and by Heath (1973) at L_α and 1750Å. Other satellite measurements of a 27-day variability of the solar flux coming from the region of the solar temperature minimum have been observed by Prag and Morse (1970) and Hinteregger (1975). The observations of Prag and Morse are not consistent with those of Heath (1973) and Hinteregger (1975). An example of the wavelength dependence of the 27-day variability observed with three channels of an experiment on Nimbus 3 (Heath, 1973) is shown in Figure 7 for a period of very high solar activity in May 1969. Since the apparent 27-day variability of the incident solar flux which originates between the transition region and the photosphere is small, it may be difficult to observe direct effects in the stratosphere and mesosphere. While the principal source of the 27-day variability of the shortest wavelength channel A in Figure 7 is L_α, that centered about 1750Å has been shown by Brueckner et al. (1976) to be quantitatively related (within 40%) to an enhanced continuum and line emission in active regions.

4. THE 11-YEAR CYCLE

The sunspot cycle, a nominal period of eleven years, is defined in terms of a modulation in the number of sunspots and sunspot groups with time. This cycle is characterized by the Wolf number, or Zurich number, R, which is a function of the total number of spots and the number of spot groups.

An 11-year solar variability is of considerable interest in the area of Sun-weather relations since many correlations with atmospheric phenomena have been reported, e.g., see the recent review by King (1975). Recently Smith and Gottlieb (1974) have concluded that there is no variation longward of 1500Å over the 11-year solar sunspot cycle.

These observations along with those obtained from a balloon flight by Brewer and Wilson (1965) indicate very definite evidence for an 11-year solar cycle variability in the ultraviolet solar flux. Observations are shown in Figure 8 as deviations from an arbitrary model of solar spectral irradiance. The observations by Heath (1973, 1976) are based on a combination of rocket and satellite measurements which began in August 1966 and extend through May 1976. The open data points corresponding to the years 1966, 1969, and 1970 represent broad-band photometric observations by the Monitor of Ultraviolet Solar Energy Experiment (MUSE) from a rocket flight in August 1966 and from the satellites Nimbus 3 and 4 which were launched in April 1969 and April 1970 respectively. These experiments were calibrated against a standard CsTe vacuum photodiode which had been calibrated by the National Bureau of Standards. The solid circle is from the measurements reported by Ackerman (1973) and the open triangle represents the balloon observation by Brewer and Wilson (1968). The crosses were obtained with a double-monochromator experiment which was flown on Nimbus 4 in April 1970 and Explorer 55 in November 1975. The latter represents the flight of a residual Backscattered Ultraviolet (BUV) Experiment flight model from the Nimbus program, a unit identical to the one launched in April 1970. Both double monochromators observed the Sun with a 10Å spectral band-pass at 12 discrete wavelengths from 2550 to 3400Å, and were calibrated against 1000 watt, quartz-iodine tungsten lamp standards of spectral irradiance.

Envelopes of the data obtained near solar maximum and solar minimum are indicated by the two solid lines in Figure 8. These observations indicate that the solar flux at 1750Å is about a factor of 2.5 greater at solar maximum than at solar minimum and at 3000Å the effect is about 18%. These changes over the solar cycle correspond to increases in the equivalent brightness temperature of the Sun of about 240°K at 1800Å and 120°K at 3000Å.

The variability which has been observed to be associated with the 11-year sunspot cycle is about a factor of 20 greater than that observed over the 27-day solar rotational period. A fundamental question remains however as to whether the variations in the UV flux over maximum and minimum phases of the solar cycle represent an increase in the total solar irradiance which is called the solar constant or whether there is a corresponding decrease in the radiation which is emitted lower down in the photosphere. In which case the "solar constant" is constant.

TITLES FOR TABLES

Table I - Major Measurements of the Solar Spectral Radiance and Irradiance in the Wavelength Range 1200 To 3000Å.

Table II - Solar Spectral Irradiance in the Wavelength Range 1000 To 3000Å. The sources of these data are: D. & P., Donnelly and Pope (1973); H. & S., Heroux and Swirbalus (1976); S. & S./A.L.B., Samain and Simon (1976) for 1510 to 2090Å and A. L. Broadfoot (1972) for 2100 to 2990Å; D. et al., Detwiler et al. (1961); M.P.T., M. P. Thekaekara (1974); B. et al., Brueckner et al. (1976); G.J.R.(1), G. J. Rottman (1974) 12/13/1972; G.J.R.(2), G. J. Rottman (1974) 8/30/1973; D. & P., Donnelly and Pope (1973) in units of 10^{10} photons s^{-1} cm^{-2} nm^{-1}.

TABLE I

MAJOR MEASUREMENTS OF THE SOLAR SPECTRAL RADIANCE AND IRRADIANCE IN THE WAVELENGTH RANGE 1200 TO 3000Å

Author - Reference	Date	Wavelength Range Å	Observing Platform	Type of Measurement	Method of Calibration
Detwiler et al. (1961)	4/19/60	850-2600	Rocket	Photographic Recording	Mt. Lemmon Measurements
Carver et al. (1972)	1967	1430-1470 1580-1640	WRESAT-1 Spacecraft	Photo Ion Chambers	Spectral Response of the System
Dupree and Reeves (1971)	Oct. 26 and 27, 1967	300-1400	OSO IV Spacecraft	Photomultiplier	Normalization to Rocket Flights
Parkinson and Reeves (1969)	9/24/68	1400-1875	Rocket	EMR Photodiode	Reeder Thermopile and Total Irr. Std.
Heath (1973)	April 70 to March 72	2550-3400	Nimbus 4 Spacecraft	Photodiode	NBS CsTe Std.
Broadfoot (1972)	6/15/70	2100-3400	Rocket	EMR Photodiode	Reeder Thermopile and Total Irr. Std.
Simon (1975)	9/23/72 and 5/16/73	1960-2300 2840-3540	Balloon	Photodiode	Reeder Thermopile and Deuterim Lamp
Rottman (1974)	12/13/72 and 8/30/73	1150-1850	Rocket	EMR Photomultiplier	NBS Calibrated Detector
Nishi (1975)	2/19/73	1400-2000	Rocket	Hamamatsu Photodiode	Spectral Response of the System
Brueckner et al. (1976)	9/4/73	1750-2100	Rocket	Photographic Recording	Deuterim Lamp and Hydrogen Arc
Heroux and Swirbalus (1976)	11/2/73 and 4/23/74	1230-1940	Rocket	EMR Photodiode	NBS Calibrated Detector
Samain and Simon (1976)	4/17/73	1510-2090	Rocket	Photographic Recording	Spectral Response of the System

TABLE II

SOLAR SPECTRAL IRRADIANCE IN THE WAVELENGTH RANGE 1000 TO 3000 Å

In ergs s^{-1} cm^{-2} nm^{-1} (11th col.: 10^{10} photons s^{-1} cm^{-2} nm^{-1}) at 1 A.U.

(See text for detailed explanations of the sources)

Wavelength Range		D. & P.	H. & S.	S. & S./ A.L.B.	D. et al.	M.P.T.	B. et al.	G.J.R. (1)	G.J.R. (2)	D. & P. Photons
From	To									
1000	1010	0.0030								0.015
1010	1020	0.0030								0.015
1020	1030	0.0709								0.3656
1030	1040	0.0805								0.4172
1040	1050	0.0028			0.002					0.015
1050	1060	0.0024								0.013
1060	1070	0.0025								0.013
1070	1080	0.0024								0.013
1080	1090	0.0132								0.072
1090	1100	0.0029			0.012					0.016
1100	1110	0.0027								0.015
1110	1120	0.0024								0.0135
1120	1130	0.0114								0.065
1130	1140	0.0018								0.01
1140	1150	0.0016			0.016	0.007				0.0092
1150	1160	0.0018								0.0105
1160	1170	0.0020						0.0163	0.0155	0.012
1170	1180	0.0394						0.0565	0.0415	0.234
1180	1190	0.0027						0.0139	0.0128	0.016
1190	1200	0.0028			1.14	0.9		0.0343	0.0247	0.017
1200	1210	0.0646						0.102	0.0940	0.392
1210	1220	5.102						5.18	3.70	31.012
1220	1230	0.0026						0.0339	0.0264	0.016
1230	1240	0.0106	0.026					0.0247	0.0202	0.066
1240	1250	0.0071	0.0150		0.03	0.007		0.0179	0.0137	0.045
1250	1260	0.0026	0.0187					0.0184	0.0166	0.016
1260	1270	0.0130	0.0187					0.0229	0.0197	0.083
1270	1280	0.004	0.0123					0.0151	0.0110	0.026
1280	1290	0.0029	0.0091					0.0116	0.0117	0.019
1290	1300	0.008	0.0115		0.036	0.007		0.0112	0.0123	0.052
1300	1310	0.068	0.069					0.111	0.102	0.44
1310	1320	0.024	0.0131					0.0198	0.0179	0.16
1320	1330	0.019	0.0135					0.0146	0.0124	0.13
1330	1340	0.106	0.049					0.125	0.111	0.71
1340	1350	0.015	0.0142		0.052			0.0127	0.0130	0.10
1350	1360	0.039	0.024					0.0312	0.0291	0.26
1360	1370	0.024	0.0184					0.0202	0.0195	0.17
1370	1380	0.023	0.0186					0.0192	0.0194	0.16
1380	1390	0.025	0.0182					0.0195	0.0198	0.17
1390	1400	0.069	0.043		0.052	0.030		0.0549	0.0587	0.48

Wavelength Range From	Wavelength Range To	D. & P.	H. & S.	S. & S.	D. et al.	M.P.T.	B. et al.	G.J.R. (1)	G.J.R. (2)	D. & P. Photons
1400	1410	0.060	0.044					0.0463	0.0483	0.43
1410	1420	0.034	0.028					0.0286	0.0292	0.24
1420	1430	0.036	0.028					0.0297	0.0337	0.26
1430	1440	0.043	0.035					0.0361	0.0375	0.31
1440	1450	0.040	0.034		0.10			0.0342	0.0389	0.29
1450	1460	0.044	0.036					0.0387	0.0435	0.32
1460	1470	0.061	0.045					0.0516	0.0524	0.45
1470	1480	0.067	0.056					0.0624	0.0674	0.50
1480	1490	0.067	0.054					0.0666	0.0700	0.50
1490	1500	0.072	0.053		0.19	0.070		0.0630	0.0622	0.54
1500	1510	0.080	0.060					0.0692	0.0717	0.61
1510	1520	0.084	0.066	0.0694				0.0727	0.0775	0.64
1520	1530	0.112	0.078	0.0786				0.0964	0.0991	0.86
1530	1540	0.13	0.088	0.0813				0.109	0.108	0.98
1540	1550	0.201	0.109	0.124	0.34			0.175	0.175	1.55
1550	1560	0.17	0.139	0.108				0.161	0.155	1.31
1560	1570	0.17	0.116	0.107				0.150	0.154	1.3
1570	1580	0.15	0.104	0.106				0.127	0.127	1.2
1580	1590	0.14	0.103	0.106				0.119	0.120	1.1
1590	1600	0.15	0.091	0.108	0.64	0.230		0.122	0.118	1.2
1600	1610	0.17	0.109	0.119				0.140	0.123	1.4
1610	1620	0.18	0.124	0.137				0.145	0.144	1.5
1620	1630	0.22	0.156	0.150				0.174	0.169	1.8
1630	1640	0.27	0.179	0.167				0.200	0.175	2.2
1640	1650	0.29	0.182	0.192	1.0			0.215	0.207	2.4
1650	1660	0.42	0.33	0.278				0.323	0.328	3.5
1660	1670	0.35	0.25	0.201				0.250	0.236	2.9
1670	1680	0.40	0.31	0.226				0.291	0.277	3.4
1680	1690	0.47	0.35	0.260				0.358	0.342	4.0
1690	1700	0.62	0.45	0.349	1.62	0.630		0.456	0.438	5.3
1700	1710	0.73	0.55	0.411				0.535	0.512	6.2
1710	1720	0.73	0.55	0.428				0.543	0.519	6.3
1720	1730	0.79	0.58	0.495				0.571	0.543	6.8
1730	1740	0.76	0.56	0.503				0.555	0.539	6.7
1740	1750	0.90	0.62	0.625	2.4		0.697	0.659	0.627	7.9
1750	1760	1.02	0.70	0.853			0.859	0.732	0.753	9.0
1760	1770	1.1	0.73	0.958			0.934	0.788	0.747	9.8
1770	1780	1.2	0.85	1.29			1.15	0.873	0.887	11
1780	1790	1.3	0.93	1.47			1.28	0.990	0.993	12
1790	1800	1.3	0.95	1.43	3.8	1.250	1.27	0.968	0.977	12
1800	1810	1.4	1.24	1.69			1.56	1.14	1.16	13
1810	1820	1.6	1.56	2.19			1.77	1.31	1.33	15
1820	1830	1.5	1.51	2.02			1.86	1.23	1.25	14
1830	1840	1.5	1.50	2.13			1.99	1.08	1.26	14
1840	1850	1.4	1.31	1.79	5.6		1.69	0.875	0.958	13

Wavelength Range		D. & P.	H. & S.	S. & S.	D. et al.	M.P.T.	B. et al	G.J.R. (1)	G.J.R. (2)	D. & P. Photons
From	To									
1850	1860	2.0	1.31	2.04			1.89			19
1860	1870	2.2	1.60	2.53			2.20			21
1870	1880	2.5	1.88	2.81			2.46			23
1880	1890	2.7	1.83	2.95			2.60			25
1890	1900	2.9	2.1	3.08	8.2	2.710	2.82			28
1900	1910	3.1	2.3	3.06			3.07			30
1910	1920	3.4	2.4	3.45			3.25			33
1920	1930	3.7	2.7	3.59			3.54			36
1930	1940	4.0	2.1	2.61			2.69			39
1940	1950	4.4		4.56	11		4.43			43
1950	1960	4.8		4.34			4.32			47
1960	1970	5.1		4.91			4.84			51
1970	1980	5.6		4.90			4.92			56
1980	1990	6.0		4.93			4.98			60
1990	2000	6.6		5.50	14	10.7	5.46			66
2000	2010	7.1		6.19			5.92			72
2010	2020	7.8		6.21			6.66			79
2020	2030	8.4		6.30			6.91			85
2030	2040	9.1		7.45			7.18			93
2040	2050	9.8		8.70	18		8.96			100
2050	2060	10.7		8.89			9.18			110
2060	2070	11.5		9.28			9.80			120
2070	2080	12.		10.8			11.5			130
2080	2090	18.		12.1			13.9			190
2090	2100	26.		A.L.B	29	22.9	20.8			280
2100	2110	37.2		39.4						394
2110	2120	46.3		44.9						494
2120	2130	39.7		41.2						425
2130	2140	43.1		50.7						463
2140	2150	55.2		53.2	48					597
2150	2160	48.3		47.3						524
2160	2170	45.3		43.0						494
2170	2180	48.9		57.5						536
2180	2190	58.9		58.2						648
2190	2200	63.3		66.7	62	57.5				700
2200	2210	61.1		52.1						679
2210	2220	52.		59.3						580
2220	2230	66.		74.8						740
2230	2240	85.5		78.4						963
2240	2250	74.7		73.7	70					844
2250	2260	66.5		60.9						755
2260	2270	49.6		45.1						566
2270	2280	51.8		63.6						594
2280	2290	66.7		62.8						767
2290	2300	58.8		58.6	72	66.7				680

Wavelength Range		D. & P.	H. & S.	A.L.B.	D. et al.	M.P.T.	B. et al.	G.J.R. (1)	G.J.R. (2)	D. & P. Photons
From	To									
2300	2310	68.3		65.3						793
2310	2320	60.5		68.1						706
2320	2330	66.4		60.4						777
2330	2340	54.9		50.7						646
2340	2350	48.1		58.3	64	59.3				568
2350	2360	67.3		62.1						798
2360	2370	59.2		62.1						705
2370	2380	62.1		52.4						743
2380	2390	50.5		58.2						606
2390	2400	54.9		51.1	68	63.0				662
2400	2410	50.7		49.9						614
2410	2420	64.		79.3						778
2420	2430	86.		82.9						1050
2430	2440	77.3		78.2						949
2440	2450	73.3		63.6	78	72.3				902
2450	2460	60.1		58.9						743
2460	2470	61.1		66.3						758
2470	2480	66.9		61.3						834
2480	2490	52.5		55.7						657
2490	2500	70.2		74.8	76	70.4				882
2500	2510	68.5		61.8						865
2510	2520	53.3		50.2						676
2520	2530	51.2		56.9						651
2530	2540	64.7		68.3						826
2540	2550	70.7		82.0	112	104.0				906
2550	2560	99.8		101.6						1280
2560	2570	120.		141.1						1550
2570	2580	144.		145.3						1870
2580	2590	148.		138.5						1930
2590	2600	115.		106.4	140	130.				1500
2600	2610	107.		96						1400
2610	2620	108.		128.						1420
2620	2630	123.		119.						1630
2630	2640	190.		270.						2530
2640	2650	279.		267.		185				3720
2650	2660	292.		288.						3910
2660	2670	269.		274.						3610
2670	2680	278.		278.						3750
2680	2690	267.		261.						3620
2690	2700	264		288.		232				3580
2700	2710	302.		283.						4110
2710	2720	234.		201.						3210
2720	2730	226.		247.						3140
2730	2740	204.		158.						2800
2740	2750	142.		164.		204				1970

Wavelength Range		D. & P.	H. & S.	A.L.B.	D. et al.	M.P.T.	B. et al.	G.J.R. (1)	G.J.R. (2)	D. & P. Photons
From	To									
2750	2760	212.		245.						2950
2760	2770	267.		273.						3710
2770	2780	244.		202.						3410
2780	2790	169.		131.						2370
2790	2800	89.8		87.1		222				1260
2800	2810	121.		175.						1710
2810	2820	244.		289.						3460
2820	2830	320.		336.						4550
2830	2840	340.		318.						4850
2840	2850	241.		155.		315				3450
2850	2860	183.		295.						2640
2860	2870	359.		380.						5190
2870	2880	358.		301.						5180
2880	2890	353.		429.						5130
2890	2900	509.		598.		482				7410
2900	2910	623.		611.						9110
2910	2920	592.		550.						8690
2920	2930	520.		562.						7670
2930	2940	554.		525.						8190
2940	2950	521.		531.		584				7730
2950	2960	585.		593.						8700
2960	2970	499.		451.						7460
2970	2980	567.		524.						8500
2980	2990	442.		497.						6650
2990	3000	496.		434.		514				7490

CAPTIONS FOR FIGURES

Figure 1. Brightness temperature T_b (legend on right - shaded area) and height in the solar atmosphere for optical depth $\tau_\lambda = 1$ above $\tau_{5000} = 1$ (legend on left - continuous line - From Vernazza et al. (1976).

Figure 2. Descriptive representation of the altitude above sea level in the Earth's atmosphere of unit optical depth for solar spectral irradiance with zero zenith angle.

Figure 3. Solar spectral irradiance in the wavelength range 1300 to 2300Å at 1 A.U.

Figure 4. Solar spectral irradiance in the wavelength range 2000 to 3000Å at 1 A.U.

Figure 5. Solar spectral irradiance in the wavelength range 2100 to 3200Å - from Broadfoot (1972).

Figure 6. Solar spectral irradiance in the wavelength range 1400 to 1750Å - from Donnelly and Pope (1973).

Figure 7. Variation in UV solar spectral irradiance per solar rotation, 100 X $(E_{max} - E_{min})/E_{min}$, observed with three sensors on Nimbus 3 near solar maximum.

Figure 8. Variations in solar spectral irradiance apparently related to the 11 year sunspot cycle based on observations from 1964 to 1975.

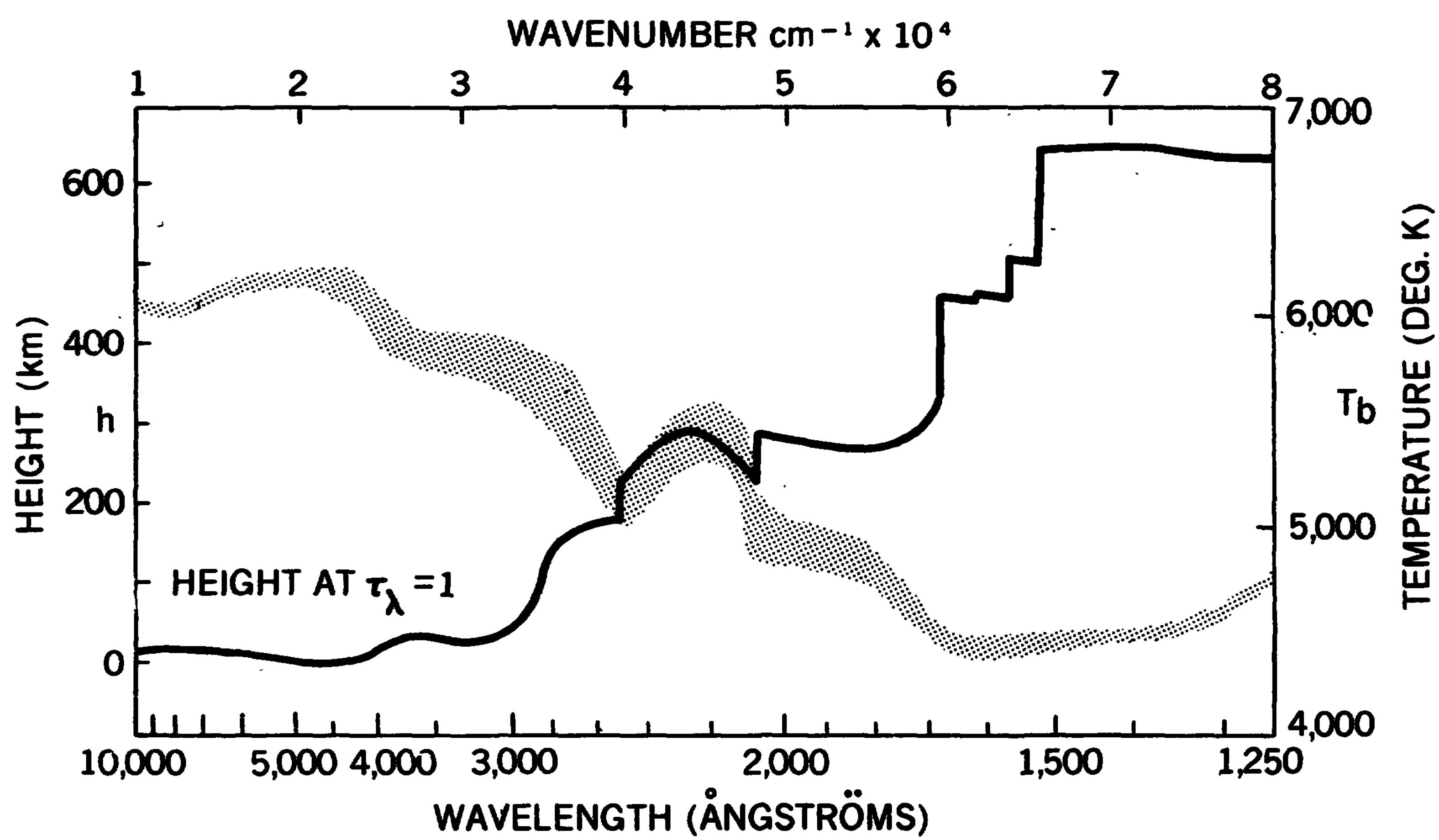

WAVENUMBER cm⁻¹ x 10⁴
1
2
3
4
5
6
7
8
600
400
h
200
0
HEIGHT (km)
HEIGHT AT $\tau_\lambda = 1$
7,000
6,000
5,000
4,000
T_b
TEMPERATURE (DEG. K)
10,000
5,000
4,000
3,000
2,000
1,500
1,250
WAVELENGTH (ÅNGSTRÖMS)

Figure !

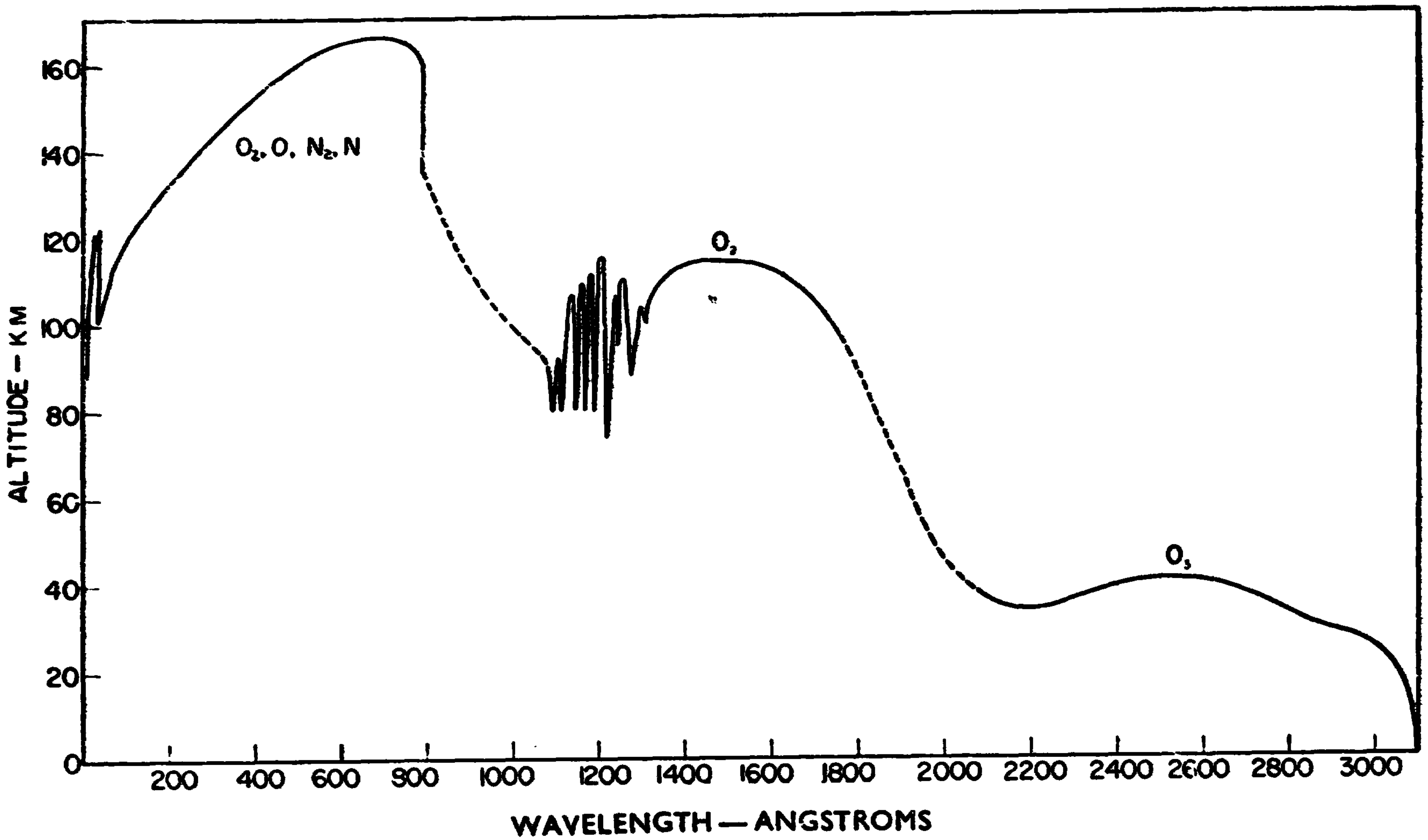

ALTITUDE - KM
160
140
120
100
80
60
40
20
0
200
400
600
900
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
WAVELENGTH — ANGSTROMS
O₂, O, N₂, N
O₂
O₃

Figure 2

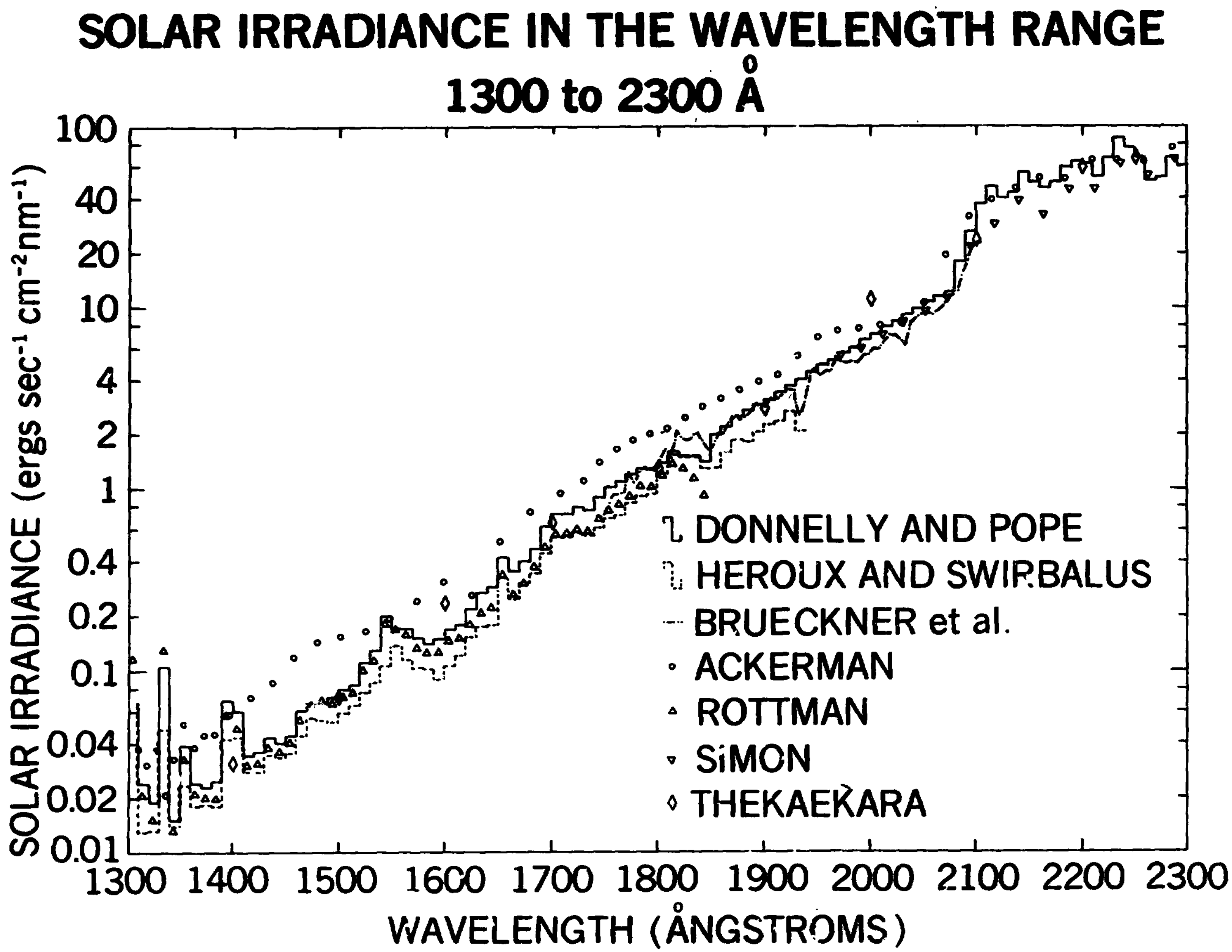

SOLAR IRRADIANCE IN THE WAVELENGTH RANGE
1300 to 2300 Å
SOLAR IRRADIANCE (ergs sec⁻¹ cm⁻²nm⁻¹)
100
40
20
10
4
2
1
0.4
0.2
0.1
0.04
0.02
0.01
1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300
WAVELENGTH (ÅNGSTROMS)
DONNELLY AND POPE
HEROUX AND SWIRBALUS
BRUECKNER et al.
ACKERMAN
ROTTMAN
SiMON
THEKAEKARA

Figure 3

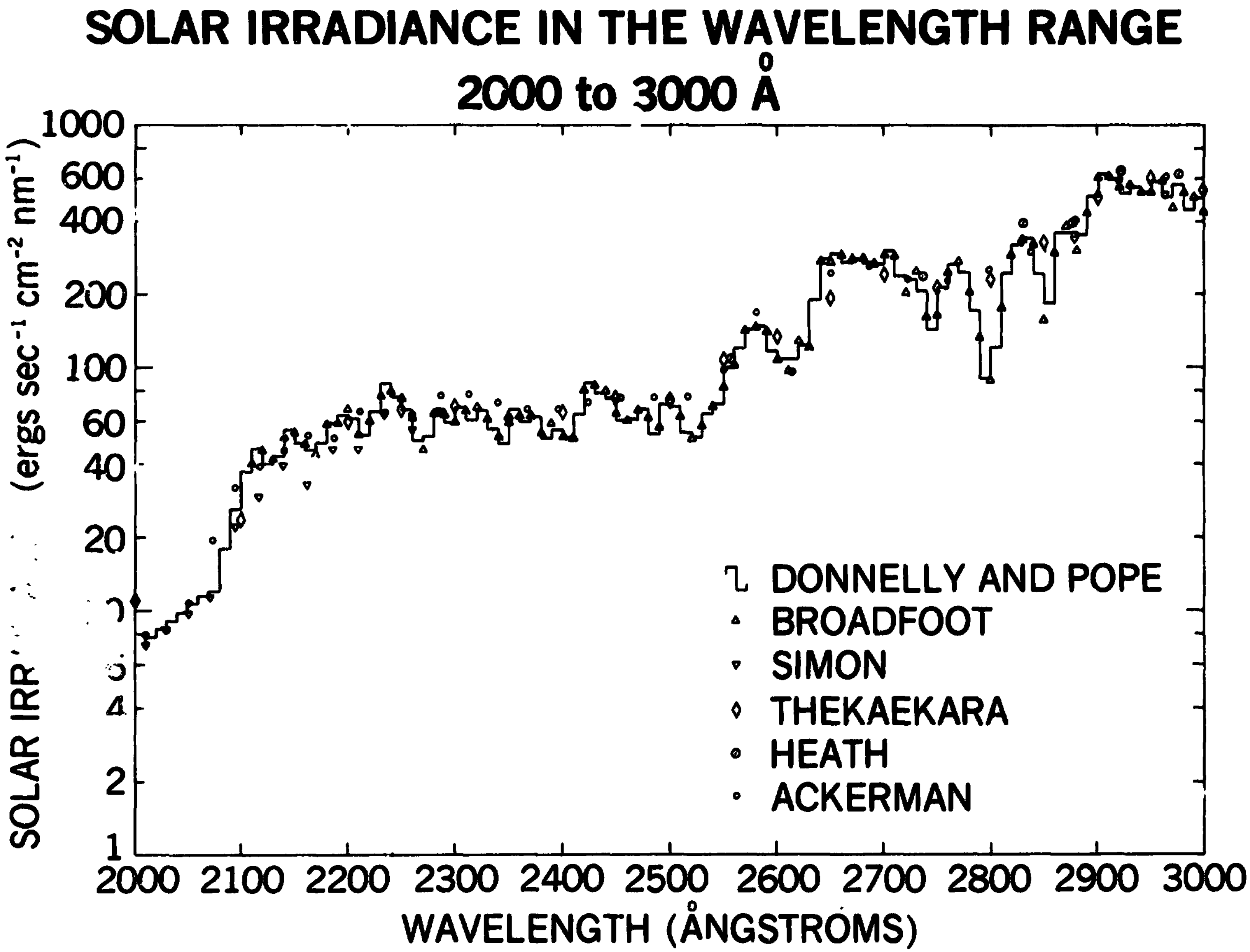

SOLAR IRRADIANCE IN THE WAVELENGTH RANGE
2000 to 3000 Å
(ergs sec⁻¹ cm⁻² nm⁻¹)
1000
600
400
200
100
60
40
20
4
2
1
2000
2100
2200
2300
2400
2500
2600
2700
2800
2900
3000
WAVELENGTH (ÅNGSTROMS)
DONNELLY AND POPE
BROADFOOT
SIMON
THEKAEKARA
HEATH
ACKERMAN

Figure 4

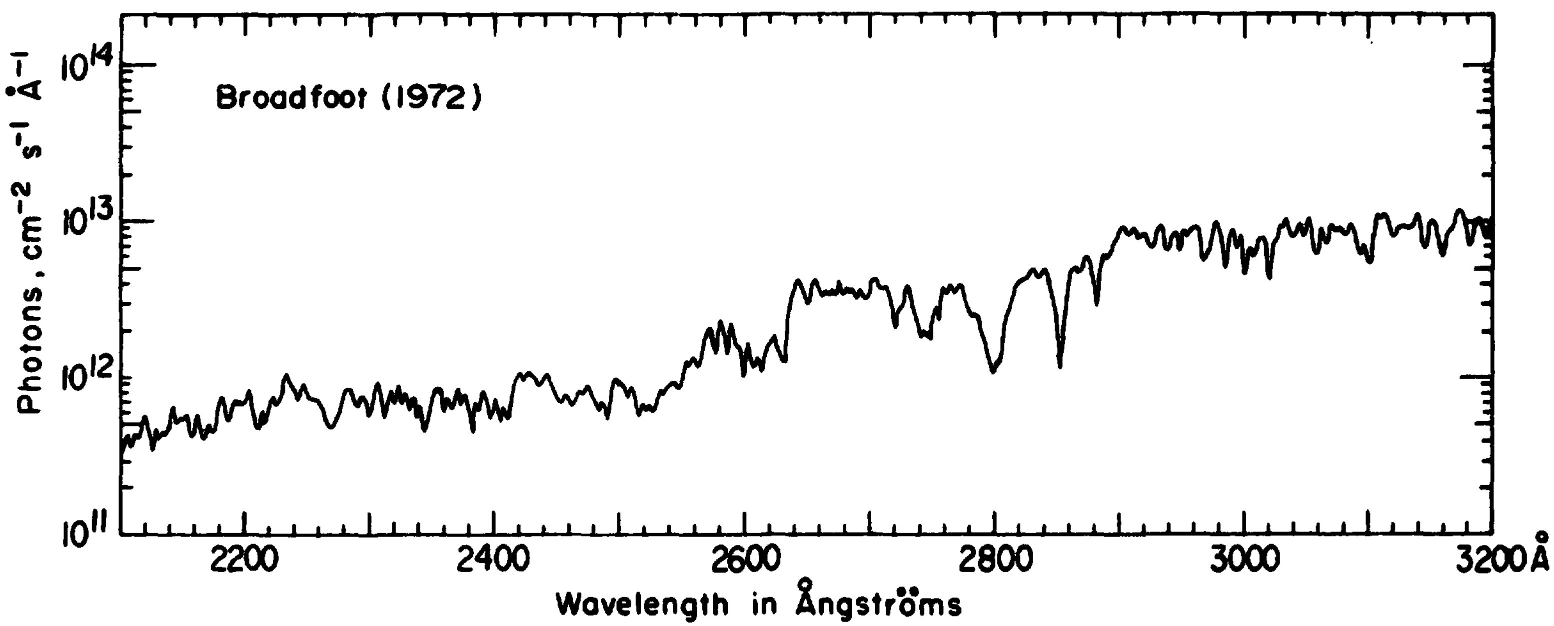

Broadfoot (1972)
Photons, cm^{-2} s^{-1} Å^{-1}
10^{14}
10^{13}
10^{12}
10^{11}
2200
2400
2600
2800
3000
3200Å
Wavelength in Ångströms

Figure 5

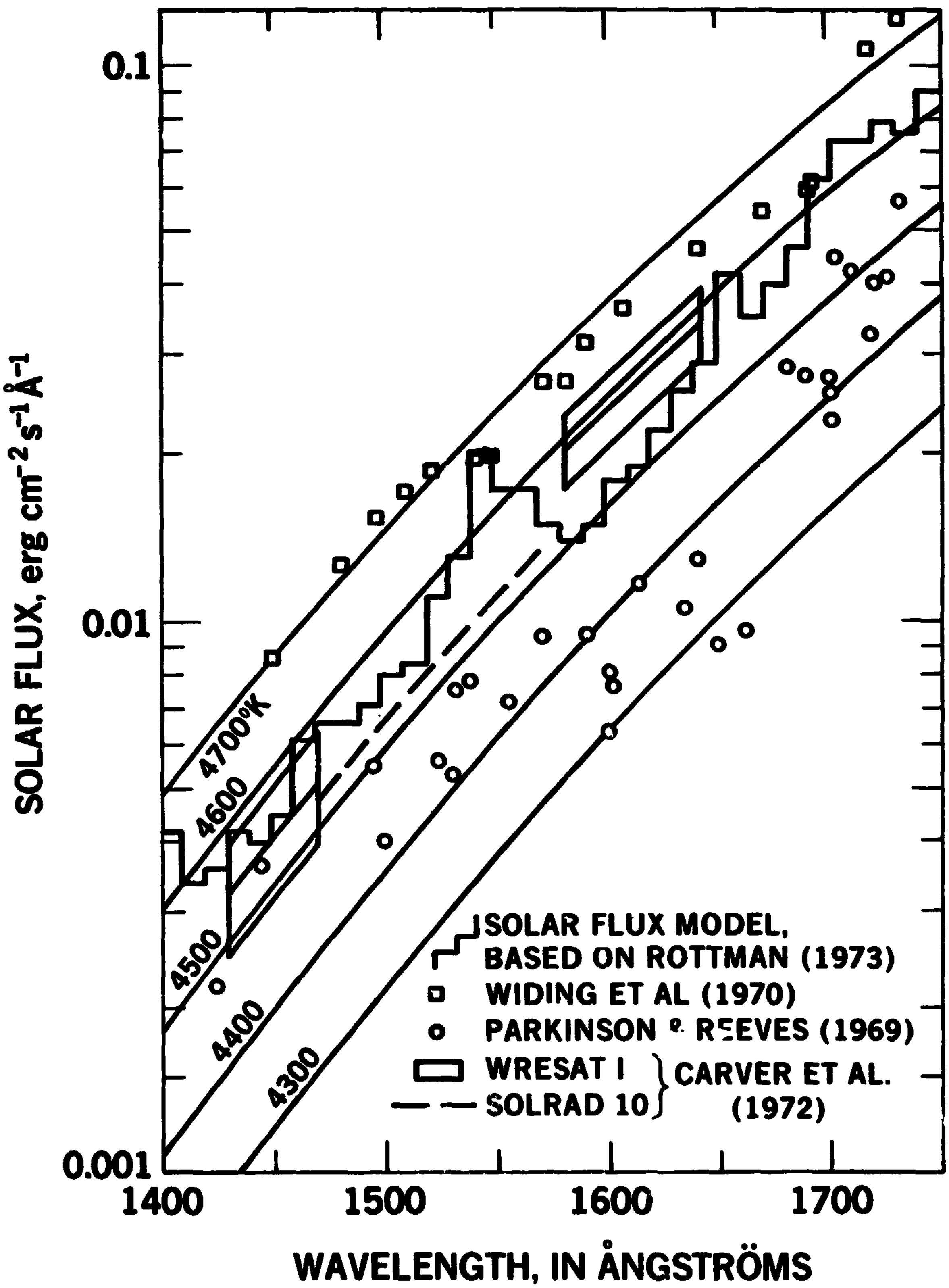

0.1
0.01
0.001
1400
1500
1600
1700
SOLAR FLUX, erg cm^{-2}s^{-1}Å^{-1}
WAVELENGTH, IN ÅNGSTRÖMS
4700°K
4600
4500
4400
4300
SOLAR FLUX MODEL, BASED ON ROTTMAN (1973)
WIDING ET AL (1970)
PARKINSON & REEVES (1969)
WRESAT I
SOLRAD 10
CARVER ET AL. (1972)

Figure 6

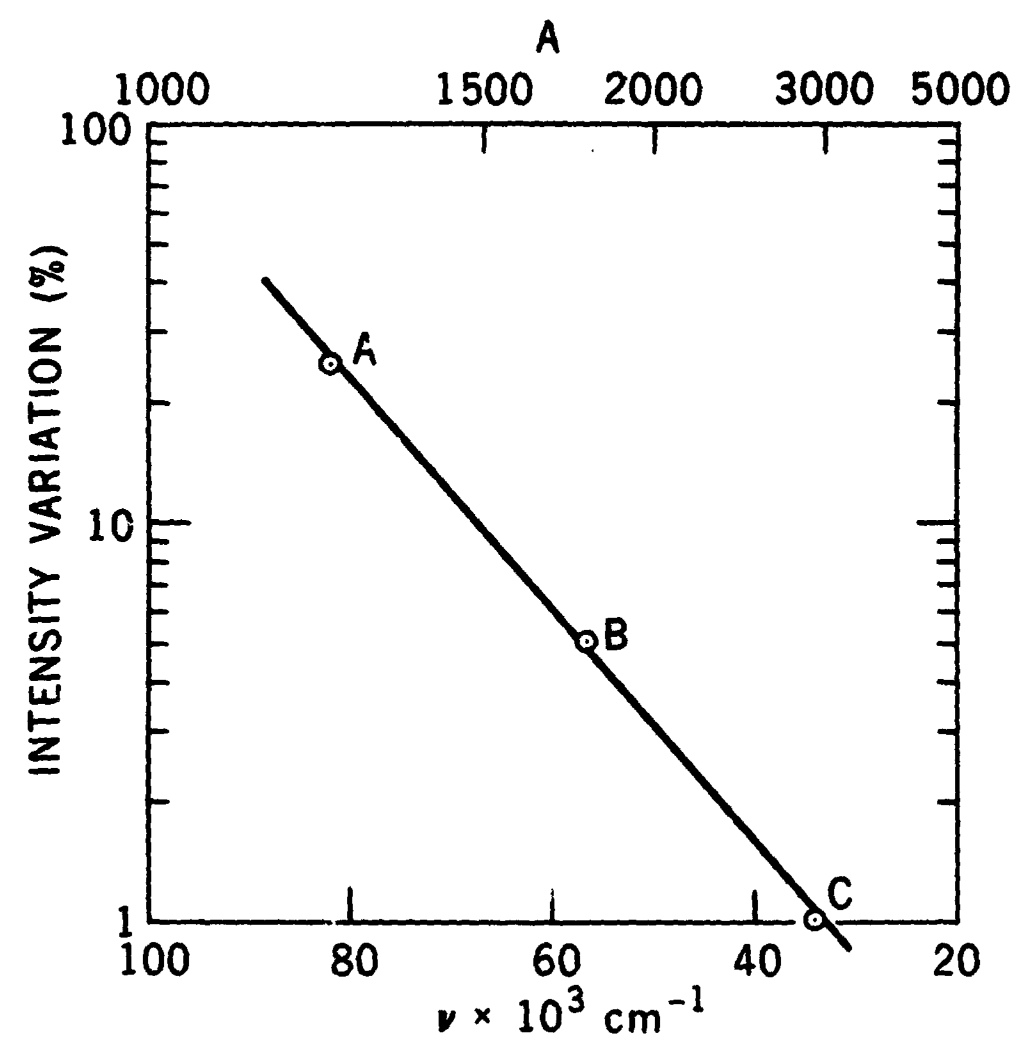
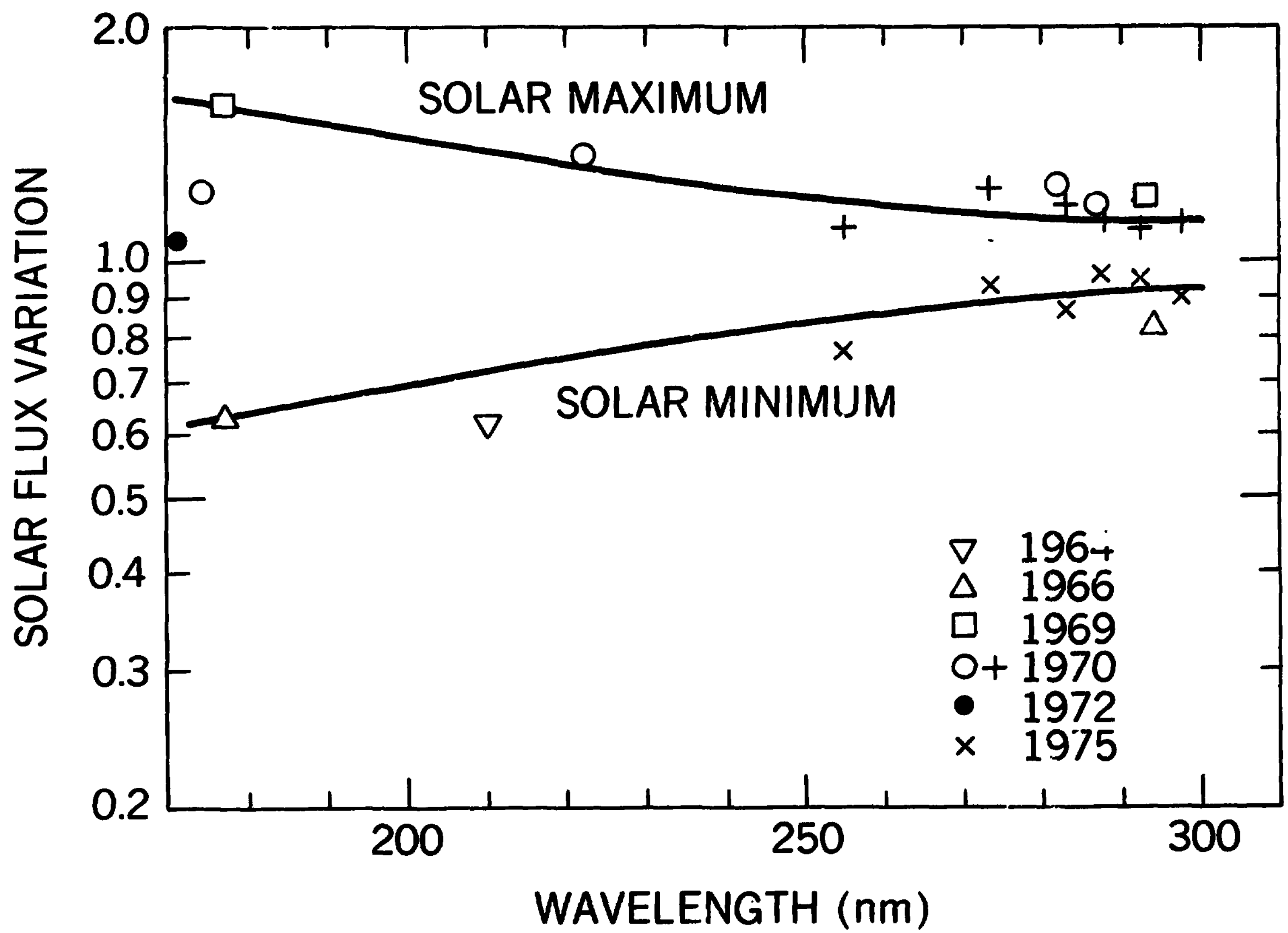

A
1000
1500
2000
3000
5000
100
10
1
INTENSITY VARIATION (%)
A
B
C
100
80
60
40
20
ν × 10³ cm⁻¹

Figure 7



2.0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
SOLAR FLUX VARIATION
SOLAR MAXIMUM
SOLAR MINIMUM
196+
1966
1969
1970
1972
1975
200
250
300
WAVELENGTH (nm)

Figure 8

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