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The Solar Constant and Spectral Distribution of Solar Radiant Flux

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ABSTRACT

A survey has been made of the data currently available on the solar constant and the spectral distribution of the solar radiant flux. The relevant theoretical considerations on radiation, solar physics, scales of radiometry and thermal balance of spacecraft have been briefly discussed. A detailed review has been attempted of the data taken by the Smithsonian Institution, the National Bureau of Standards and the Naval Research Laboratory, of the methods of data analysis and the many revisions of the results. The survey shows that the results from different sources have wide discrepancies, that no new experimental data have been taken in recent years, and that the conventional technique of extrapolation to zero air mass leaves large uncertainties. The feasibility of further measurements and of a new method of approach has been discussed in the light of the results of this survey.

I. INTRODUCTION

The solar constant and the spectral distribution of the solar radiant flux are of considerable importance in many areas of physics and engineering. In geophysics and meteorology, in studies of the upper atmosphere and of the thermal balance of the earth, in the investigation of solar phenomena and in many areas of illuminating engineering, the radiant energy received from the sun is a significant parameter. In recent years the topic has received a great deal of attention because of its bearing on the thermal balance of spacecraft.

In spite of the widespread interest in the subject and its importance in many areas of scientific research, no new experimental data have been collected in recent years. It is generally assumed that the best value of the solar constant available at present is 2.00 cal. cm^{-2} min^{-1}. This value was deduced by Francis S. Johnson at the Naval Research Laboratory, Washington D. C. in 1954[1]. It is based on revisions of data which had been collected for over 30 years by the Smithsonian Institution, later data collected by Dunkelman and Scolnik[2] in 1951, and a reevaluation of the correction factors for the infrared and ultraviolet regions of the spectrum.

It is interesting to observe that the solar constant has frequently been revised, and each new revision has increased its value. Parry Moon[3] in 1940 published a detailed analysis of the data of the Smithsonian Institution and arrived at the value 1.896 cal. cm^{-2} min^{-1}. A revision in 1952 by Aldrich and Hoover[4] raised the value to 1.934 cal. cm^{-2} min^{-1}. C. W. Allen[5], in 1955 gave a value, 1.[illegible] $\pm$ .01 cal. cm^{-2} min^{-1} and Francis S. Johnson's value, as stated earlier, was 2.00 $\pm$ .004 cal. cm^{-2} min^{-1}. An independent set of measurements was made by Ralph Stair and Russell G. Johnston[6] at an altitude of 9200 feet; they published in 1956 a still higher value, 2.05 cal. cm^{-2} min^{-1}.

The discrepancies between different investigators are even greater for the published data on the spectral distribution of the radiant flux. Some of the more reliable data have been collated and published by P. R. Gast[7] in the "Handbook of Geophysics", where he makes the following observation: "As an example of a more important uncertainty, in the ultraviolet region (300 to 359 $m\mu$), the discrepancy between various observations is about 10 per cent, and there have been reported[8] variant observations as large as 40 per cent which can be neither ignored nor explained."

In this paper an attempt will be made to present the relevant theoretical considerations and to collect together and evaluate the available information on the solar constant and the solar spectral radiant flux. The feasibility of further measurements will be studied in the light of existing data.

II. THEORETICAL CONSIDERATIONS

1. Terminology and Laws of Radiation

There is no uniformity in the literature concerning the terms and symbols used for the physical quantities involved in the statement of radiation laws. In recent years many authors have shown a preference for "The American Standards Nomenclature for Radiometry", ASA Z 58.1.1 - 1953[9], which was proposed by the American Standards Association Sectional Committee, Z - 58. This Committee had been sponsored by the Optical Society of America and the proposed nomenclature was approved on February 27, 1953. This nomenclature will be followed here.

Radiant energy density or radiant density, u, at a given point in space is the energy per unit volume in the vicinity of that point.

The radiant flux, P, through a given surface is the radiant energy which crosses unit area in unit time.

The radiant emittance (or flux density), W, of a radiating surface at a given point is the radiant energy emitted per unit area in the vicinity of that point per unit time.

The radiance, N, of a radiating surface at a given point in a given direction is the radiant energy emitted per unit area, per unit solid angle in that point, per unit time.

Related quantities are radiant reflectance, ρ, transmittance, τ, and absorptance, α, which are the ratios of energy reflected, transmitted and absorbed, respectively, to the energy incident.

Emissivity, of a given surface ε, is the ratio of the radiant emittance of the surface to that of a blackbody surface at the same temperature.

The solar constant is the radiant flux due to the sun which crosses unit area exposed normally to the sun's rays at the average distance of the earth from the sun.

The above quantities refer to the energy radiated at all frequencies or in the entire wavelength range. The corresponding spectral quantities are denoted by adding the subscript λ, for wavelength, or ν, for frequency, to the respective symbol.

The spectral radiant flux P_λ, for example, is related to the radiant flux P by the equation $P = \int_0^\infty P_\lambda \, d\lambda$.

Certain simple relations hold between the quantities P, W, u, and N, if the radiating surface is perfectly diffuse, that is, if it has a constant radiance in all directions. These relations are:

$W = \pi \Omega_0 N$, where Ω_0 is one steradian;

$u = \dfrac{4\pi\Omega_0 N}{c}$, where c is the velocity of light; and

$W = \dfrac{cu}{4}$.

For collimated radiation, P = cu. The Planck's law gives the spectral radiant density in terms of the temperature, as

$$u_\lambda = \frac{8\pi h c}{\lambda^5\left(e^{hc/\lambda k T} - 1\right)} \quad (1)$$

The Stefan - Boltzman law gives the radiant emittance of a blackbody surface as $W = \sigma T^4$, where $\sigma = \frac{2}{15} \frac{\pi^5 k^4}{c^2 h^3}$. (2)

This may be derived from Planck's law by integrating the right hand side of equation (1).

From Planck's law may also be derived, by differentiating the right hand side and equating it to zero, the Wien displacement law which states that the wavelength at which the spectral distribution of the radiant emittance of a blackbody is maximum varies inversely as the temperature. $\lambda_{max.} T$ is a constant, equal to 0.289776 cm degree K.

The above equations of a blackbody radiation are applicable to the solar radiant flux though only to a first order of approximation. If the effective temperature of the sun's radiating surface and the area of the radiating surface are accurately known, both the solar constant and the spectral solar radiant flux can be determined from purely theoretical considerations. But these quantities do not permit a precise definition, nor can they be determined experimentally with sufficient accuracy.

The different parts of the sun which are responsible for the energy received from the sun are distinguished as the photosphere, the reversing layer, the chromosphere and the corona. The photosphere is the sun's surface directly visible in a telescope or a darkened glass. The opacity of the gases in this layer increases rapidly with depth, and hence prevents us from seeing farther into the sun. Even with the best of telescopes the edge of the photosphere at the circumference of the solar disc appears very sharp; hence we conclude that the transition from maximum brightness to total opacity occurs within a relatively short distance of about 50 km. This explains the close similarity of the solar spectrum to that of blackbody radiation.

The reversing layer and the chromosphere together form the atmosphere of the sun. They consist of luminous but very transparent gases. The reversing layer expends to a few hundred miles and the chromosphere to a height of several hundred miles. The chromosphere, consisting mainly of hydrogen and helium, is a partial absorber of solar radiation, but its effect is small compared to the more dense reversing layer. The reversing layer contains vapours of almost all the familiar elements of the earth's crust. The strong absorption of energy by the reversing layer is mainly responsible for the departure of the spectral radiant flux of the sun from that of a blackbody.

The corona may be considered the extreme fringes of the solar atmosphere. The luminous part of the corona, as seen during a total eclipse, extends to a height of several solar radii. But recent experiments with space probes have shown that the corona has no distinct outer boundary, and that even the earth's orbit is enclosed within a tenuous coronal region. Hence the attenuation of energy in the sun-earth distance is greater than in the more rarefied regions of interstellar or intergalactic space.

There are several other factors which affect the total and spectral radiant flux of the sun. Among these are the sunspots which have a periodicity of eleven years, the faculae and the prominences which are relatively unpredictable, and the more permanent inhomogeneities of the photosphere. Thus we conclude that many complex radiative processes of emission and absorption combine to make the energy received at the average distance of the earth to be significantly different from that of balckbody radiation.

2. Solar Simulation and Thermal Balance of Spacecraft

In the area of solar simulation and thermal balance of spacecraft, the above theoretical considerations of blackbody radiation laws and solar radiant flux are of great importance. A question of special significance is the degree of error and inaccuracy in the predicted equilibrium temperatures of satellites, caused by errors in the assumed values of the solar constant and the solar spectral radiant flux. A complete discussion of this problem in any actual case involves many, highly complex and variable parameters. Among these parameters are the planet radiation of the earth, the reflected solar radiation from the earth, cloud cover and meteorological conditions, relative duration of the satellite inside and outside the earth's shadow, the ellipticity of the satellite orbit round the earth, the ellipticity of the earth's orbit round the sun, the external geometry of the satellite, the internal transfer of heat between satellite components, and the properties of the exposed surface of the satellite as regards absorption of radiation and its reemission.

In our discussion of the problem we shall ignore the radiation from the earth. It is also permissible to treat many of the other parameters as a constant, independent of the solar radiant flux. For the sake of mathematical simplicity we shall consider first the case of a flat disc and that of a sphere, and extend the conclusions to a few other more general cases.

Let A be the surface area of the disc, and let the thickness of the disc be negligibly small compared to A. Let the disc be coated with an ideal black paint. Hence the surface is a perfect absorber and emitter, so that the radiant emittance is given by the Stefan - Boltzman law, equation (2) and all the solar energy incident on the surface is absorbed by it. If the exposed area is normal to the solar radiant flux, the energy absorbed is PA, where P is the solar radiant flux. The energy radiated by the body is

$$2 A \sigma (T^4 - T'^4)$$

where T is the temperature of disc and T' is the ambient temperature. Since T and T' are respectively of the order of 300° K and 4° K, T'^4 is about 10^{-7} times T^4, and is negligible in comparison to T^4. Let T be the equilibrium temperature. Since the heat absorbed is equal to the heat radiated,

$$2\,A\,\sigma\,T^4 = PA\;; \tag{3}$$

i.e., $T^4 = \dfrac{1}{2\,\sigma}\;P.$

Differentiating both sides,

$$4\,T^3\,dT = \frac{1}{2\,\sigma}\;dP. \tag{4}$$

Dividing equation (4) by equation (3),

$$dT/T = 1/4(dP/P)\,. \tag{5}$$

Hence for a perfectly flat disc, the percentage error in the predicted value of equilibrium temperature, on the Kelvin scale, is one-fourth the percentage error in the assumed value of the solar constant.

It may readily be shown that equation (5) is independent of the geometrical shape of the body, and holds true for all cases of a perfectly black surface, with no internal heat sources or heat sinks.

If the body is spherical of radius R, the effective absorbing area is the area of cross-section πR^2, and is one-fourth the total emitting area. Hence equation (3) should be changed to $T^4 = (1/4\sigma)P$; the equation (5) is unchanged. For a cube having one of its six surfaces normal to the solar radiation, the equation of thermal balance corresponding to equation (3) is $T^4 = (1/6\sigma)P$. For a spinning body of arbitrary shape, the only term that needs modification is the area of the absorbing surface, which is the time average of the area of cross-section normal to incident radiation.

The above results may be illustrated by a few numerical examples. The Stefan - Boltzmann constant, σ, is 5.6693×10^{-5} erg cm^{-2} s^{-1} $(^{\circ}K)^{-4}$, the solar constant, P, is assumed to be 0.1395×10^{7} erg cm^{-2} s^{-1}. Substitution of these values in equation (3) gives the equilibrium temperature of a disc to be 331.1°K or 60.1°C. An increase of ten per cent in the assumed value of the solar constant would increase the predicted equilibrium temperature to 68.1°C, and a decrease of ten per cent would lower the predicted value to 51.4°C.

For a spherical body, the ratio of the absorbing area to the emitting area is half that of a flat disc, and the equilibrium temperatures are lower. The predicted values are 7°C, 13.4°C and -0.2°C respectively for assumed solar constant 0.1395, 0.1535 and 0.1256 watts cm^{-2}.

Actually the surfaces of satellites are not perfect absorbers or emitters, and hence it is necessary to introduce the expressions for absorptance and emissivity into the equations of thermal equilibrium. Both absorptance and emissivity are to be distinguished as total and monochromatic. The relations between the different quantities can be best expressed by the following equations:

If $P'_\lambda \, d\lambda$ is the energy incident in the wavelength range λ to $\lambda + d\lambda$, the energy absorbed in the same range is $P'_\lambda \alpha_\lambda \, d\lambda$. (The prime indicates that the radiant flux has a spectral distribution different from that of a blackbody). The total energy absorbed is $\int_0^\infty P'_\lambda \alpha_\lambda \, d\lambda$, and the total incident energy is $\int_0^\infty P'_\lambda \, d\lambda$. The ratio of the two integrals is the total absorptance α . The definition of the absorptance of a surface is thus necessarily with reference to a specific spectral distribution of the incident radiant flux. In particular, solar absorptance values differ according as one considers the absorptance at sea level or for zero air mass and according as one or another of the accepted solar spectral radiation functions is used for performing the integration. Solar absorptance is determined either by exposing specimens to sunlight and measuring the energy absorbed or by calculating the value from known functions of α_λ and P'_λ .

The radiant emittance from a non-blackbody surface is given in terms of that from a blackbody surface at the same temperature by the equation

$$W' = \int_0^\infty W'_\lambda \, d\lambda = \int_0^\infty \varepsilon_\lambda W_\lambda \, d\lambda = \varepsilon \int_0^\infty W_\lambda \, d\lambda = \varepsilon W . \tag{6}$$

ε and ε_λ are respectively the total emissivity and the spectral emissivity.

The equation for temperature equilibrium for a body which is not a perfect absorber or emitter is

$$\varepsilon A_{\varepsilon} \sigma T^4 = \alpha A_{\alpha} P' . \qquad (7)$$

A_{ε} and A_{α} are respectively the areas of the emitting surface and the absorbing surface.

The equilibrium temperature depends not only on the ratio $A_{\alpha} / A_{\varepsilon}$ as discussed earlier, but also on the ratio α / ε. For numerical examples, we might consider two extreme cases of α / ε equal 16 or 1/16. These numbers are respectively 2^4 and 2^{-4}. The corresponding equilibrium temperatures of a flat disc are respectively 666.2°K and 166.6°K. In actual cases α / ε does not vary over such wide ranges. For white paint representative values are $\alpha = 0.22$; $\varepsilon = 0.88$; for evaporated gold, $\alpha = 0.07$; $\varepsilon = 0.02$. It is important to note that the temperatures with reference to which are measured the two ratios α and ε, are very different. The emissivity refers to the actual temperature of the satellite. The definition of α assumes the spectral energy distribution of a body at a relatively high temperature, 6000°K.

In so far as the calculation of α is dependent on the assumptions regarding the solar constant and the solar spectral radiant flux, the degree of error in these values causes a corresponding error in the predicted values of the equilibrium temperature. However, this is a second order effect since α is the ratio of the two integrals, $\int_0^{\infty} P'_{\lambda} \alpha_{\lambda} \, d\lambda$ and $\int_0^{\infty} P'_{\lambda} \, d\lambda$.

This becomes significant only in cases where α_{λ} is very highly wavelength dependent, as may well happen with specially prepared surfaces of very thin multilayer coatings. Reference may be made in this connection to the extensive studies made by the Armour Research Foundation (WADC Technical Report, May 1957) on solar absorptances at sea level and for zero air mass of a large number of standard aircraft materials. These data have been cited in a review of literature entitled

"Thermal Radiation Properties Survey," by G. G. Gubareff, J. E. Janssen and R. H. Torborg, published in 1960 by Honeywell Research Center, Minneapolis, Minnesota[10]. Over 70 different types of surfaces have been examined, mostly metal surfaces with different grades of polishing, and a few surfaces of graphite and plastic laminate. The difference between α at sea level and α above the atmosphere is of the order of one or two percent for surfaces having α greater than 0.4. Large percentage differences of 5 to 35 per cent occur in cases where α is small, as for example copper, aluminum and magnesium alloys. For copper and magnesium alloys the absorptance at sea level is lower than that above the atmosphere and for aluminum it is higher. The uncertainties in our current knowledge of the solar spectral radiant flux are the greatest in the wavelength range below 3600 A, and unfortunately this is also the range where the spectral absorptance of most satellite coatings are highly wavelength dependent. As stated earlier the percentage error in the predicted temperature in degrees Kelvin is one fourth the corresponding percentage error in the assumed values of α or P. The errors are cumulative.

Given the large variety of the external shape and the surface coating of spacecraft, it is not possible to draw any more specific conclusions about the degree of error in predicted equilibrium temperatures. Those engaged in prelaunch testing in solar simulators and in theoretical computations of predicted temperatures should have at hand the values as accurate as possible, of the solar constant and the solar spectral radiant flux. And more importantly they should have an estimate of the possible errors in the accepted values of these quantities.

3. Standard Scales of Radiation Measurement

One of the major problems in all measurement of energy is the standard scale with reference to which the energy measurements are reported. Internationally accepted standards exist for fundamental units like length and mass and for many of the derived units like ampere and volt. As for total radiant flux and spectral radiant flux, different countries use different standards, and intercomparisons between them show that they differ among each other by one or two per cent.

For the sake of clarity the question of a standard may be put thus: when can one say that a certain length is one meter, that a certain current is one ampere or that a certain radiant flux is one watt per cm^2? The answer about the meter and the ampere are given unambiguously, with a high degree of accuracy, and is accepted by international commissions. The meter is defined in terms of a spectral line of krypton, and the ampere in terms of the amount of silver deposited by a standard cell. There is no such internationally accepted standard for energy.

A secondary standard of spectral radiant energy most widely used in the U.S. is the tungsten ribbon lamp operated at a specified current [11]. The calibration table supplied along with the lamp gives the spectral radiance of the incandescent ribbon at a large number of wavelengths. The physical quantity which is measured in the process of calibration is the color temperature of the ribbon at one or more wavelengths. The color temperature is determined with reference to a blackbody of known temperature. From known values of the emissivity of tungsten, transmission coefficient of the envelope of the lamp and blackbody radiation functions, it is possible to calculate the spectral radiance from the color temperature. Relatively large errors may be introduced into the calculations because of the poor accuracy with which the emissivity of tungsten and the color temperature are determined. The calibration tables of the tungsten standard ribbon lamps do not claim an accuracy better than 5 per cent. This may perhaps be a conservative estimate. No attempt has been made to establish an international standard for spectral radiance.

The situation is slightly better for total radiant flux[12]. The standard in this case is not a source of radiant flux but an instrument for measuring radiant flux. In other words, a standard scale of radiant flux is established giving the incident energy (in watts per cm^2) in terms of a more readily measurable physical quantity, temperature (in degrees C) or current (in amperes) generated in a given instrument. Most of this work of standardization has been done in connection with the measurement of solar energy, and the instrument is the pyrheliometer.

In meteorological institutes measurements of total radiant flux are usually standardized with reference to one or the other of two standard scales. For the sake of brevity we shall refer to them as the Smithsonian scale and the Ångström scale. Both scales have been periodically revised and considerable work has been done in comparing them with each other and with other independent radiation scales. A brief description of the instruments and the standardization procedures will help clarify some of the confusion concerning radiation measurement and will show the degree of error in such measurement.

The Smithsonian scale is defined with the aid of the Abbot silver disc pyrheliometer. A silver disc is exposed to solar radiation and the rise in temperature of the disc is measured. To convert the temperature rise in ^{o}C to energy in watts per cm^2, a calorimeter is exposed to the same radiation and the heat absorbed by the calorimeter is determined. The Ångström scale is defined with the aid of the Ångström compensated strip pyrheliometer. One of two similar metallic strips is exposed to solar radiation and the other is heated by an electric current; the value of the current is adjusted until both the strips are at the same temperature. From known values of the resistance of the strip and the absorptance of its surface it is possible to establish a standard scale of radiant flux in watts cm^{-2} in terms of the current in amperes.

In 1932, the Smithsonian Institution introduced an improved form of calorimeter, and reexamined the accuracy of the scale which had been in use since 1913. The result of this study was that the Smithsonian announced that the measurements made on the 1913 scale had been 2.5% too high. This finding was confirmed by later measurements made in 1934, 1947 and 1952. However, the Smithsonian continued to standardize instruments in terms of the1913 scale so as to preserve continuity.

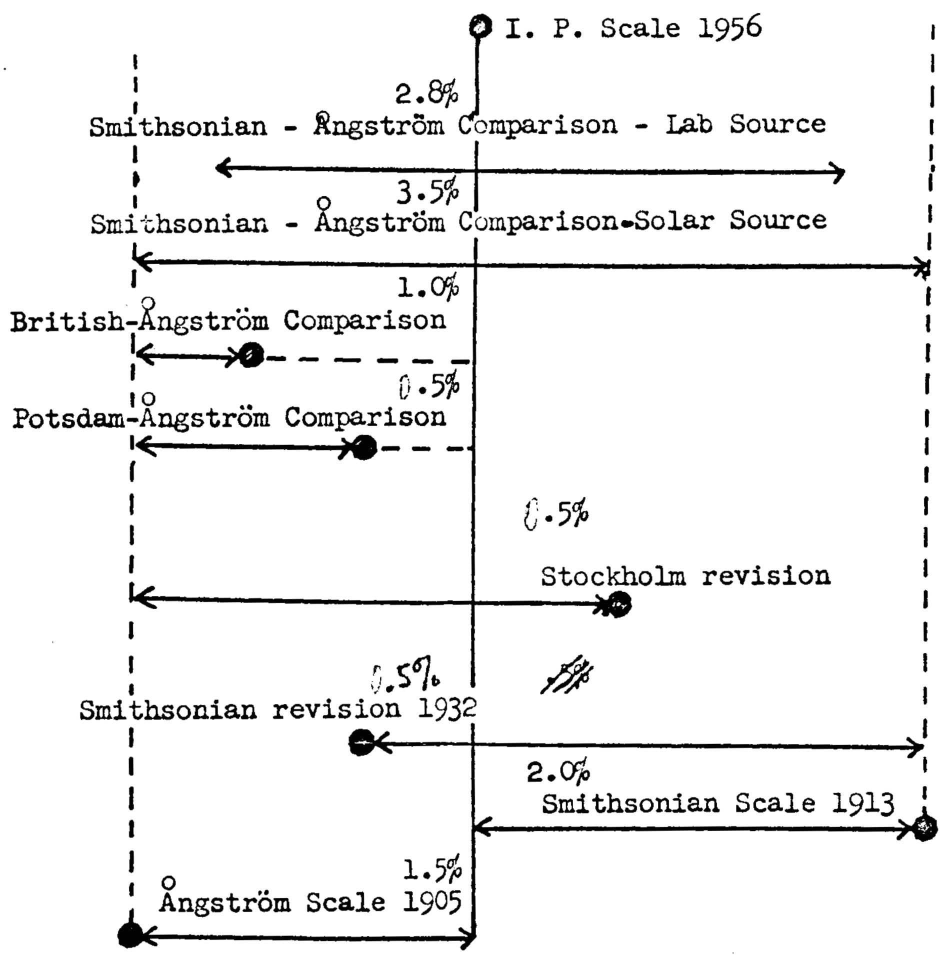
The Ångström scale was originally established in 1905. It is based on two main types of instruments. For one type of instruments the original calibrations were made at Uppsala, Sweden, and now they are being made at Stockholm, Sweden; the source of energy is the sun and the conversion from current in amperes to energy in watts cm^{-2} is made from the known parameters of the instrument. For the other type of instruments the calibration is made at the Smithsonian Institution, with the sun as source and the standard calorimeter as the reference, in the same manner as for the Abbot silver disc pyrheliometer. We shall refer to the absolute scale established by the Uppsala-Stockholm group as the Ångström scale. The original scale established in 1905, was later found to be in error due to several causes, in particular, "the edge effect," namely that the edges of the exposed strip receive no radiation. Extensive studies made at Stockholm in 1956 and preceding years showed that the measurements made on the Ångström 1905 scale were 2% too low.[13]

Thus a reading Smithsonian 1913 scale is to be lowered by 2.5%, and that on the Ångström 1905 scale is to be raised by 2% to give the correct value of radiant flux. If the experiments on which these results are based are accurate, we would expect that a substandard instrument calibrated on both the Smithsonian 1913 scale and the Ångström 1905 scale should give different readings according to which scale is used; the reading on the Smithsonian scale should be 4.5% higher than the reading on the Ångström scale. Several such comparisons of the two scales have been made using sub-standard instruments with the sun as source. The differences are not constant, but show a large scatter; and the mean of the differences is 3.5% and not 4.5% as we would expect. One explanation for this may be that different instruments when directed at the sun do not always view the same fraction of the circum-solar atmosphere. Laboratory sources should be free from this source of error. A few measurements have been reported using a laboratory source instead of the sun as the source of radiant flux. The average of the differences between the two scales is even lower, namely, 2.8 per cent. This has been explained as probably due to another source of error, introduced by the relatively weak laboratory source; the area of the Abbot silver disc of the Smithsonian instrument is too large and does not receive a uniform distribution of energy when exposed to a laboratory source.

Comparisons have been made also between the Ångström 1905 scale and two other independent, so-called standard scales, one British and the other East German, both of which are claimed to be absolute, that is, to give radiant flux in watts cm^{-2}. A laboratory comparison between the British standard scale maintained at the National Physical Laboratory and a sub-standard representing the Ångström 1905 scale showed that the latter is lower by 0.5 per cent. A series of intercomparisons, using the sun as source, were made in 1934 at Davos, Switzerland, between the absolute pyrheliometer (a calorimeter) maintained at Potsdam, Germany and a substandard representing the Ångström 1905 scale. These studies showed that the Ångström 1905 scale was too low by 1 per cent. Neither of these differences comes up to the 2 per cent which according to the Stockholm Institute is the correction to be applied to the Ångström 1905 scale.

The International Radiation Conference held in 1956 at Davos, Switzerland, recommended the adoption of a new scale of radiation to replace the Smithsonian 1913 scale and the Ångström 1905 scale. This scale was adopted by the World Meteorological Organization, to be effective from January 1, 1957, and is known as the International Pyrheliometric Scale 1956, which we shall write as I. P. scale 1956. By definition of this scale, to express pyrheliometric measurements on the I. P. scale 1956, the measurements on the Ångström 1905 scale should be increased by 1.5 per cent and the measurements on the Smithsonian 1913 scale should be decreased by 2.0 per cent.

The relation between the I. P. scale 1956 and the other scales is shown in the following diagram.



Each black dot represents a scale of radiation, and its relative distance to the right or to the left of the vertical line shows by what percentage the readings on that scale are higher or lower than the readings on the International Pyrheliometric (I. P.) scale 1956. By definition of the I. P. scale 1956, the Ångstrom 1905 scale is low by 1.5%, and the Smithsonian 1913 scale is high by 2.0%. The Smithsonian revision of 1932 makes the Smithsonian 1932 scale 0.5% lower than the I. P. scale 1956. The Stockholm revision makes the corrected Ångstrom scale 0.5% higher than the I. P. scale 1956. Both the British and German scales are lower than the I. P. scale 1956.

These relatively large differences between the different scales should be borne in mind when comparing the values of the solar constant given by different authors.

A question of special interest is: on what scale is based the Johnson value, 2.00 cal cm^{-2} min^{-1} of the solar constant? What Johnson attempted was a revision of the Smithsonian data. According the Smithsonian, the solar constant, on the scale of 1913, is 1.981 cal cm^{-2} min^{-1}. But readings on this scale are too high. Aldrich and Hoover[4] stated in a paper in 1952 by how much the value should be lowered; the amount is 2.37 per cent, which is slightly less than the 2.5 per cent of the 1932 revision. It is this correction that Johnson accepted as a starting point: 1.981 (1 - 0.0237) = 1.934. Thus the Johnson value is based on 1956 a scale 0.37 per cent lower than the International Pyrheliometric Scale ~~1957~~ 1956.

III. REVIEW OF MAJOR CONTRIBUTIONS

1. Smithsonian Institution

The most extensive investigations on the solar constant and the spectral distribution of solar radiant flux are those made by the Smithsonian Institution of Washington, D. C. The work was started at the beginning of the century, and was continued for over fifty years.

The main steps of the Smithsonian procedure are shown in figure 1, which is adapted from Johnson[1] and Tousey[14]. There are two independent measuring instruments, one a pyrheliometer which measures the total energy without any spectral resolution, and the other, a spectrobolometer which measures on a relative scale the solar spectral radiant flux. The pyrheliometer reading is used for converting the relative values of the spectrobolometer to an absolute scale. But the two instruments do not have an identical wavelength range. The spectrobolometer is limited to the wavelength range 0.346 to 2.4 microns, whereas the pyrheliometer registers the energy of the entire spectrum as transmitted by the atmosphere. Hence one has to add to the integrated area under the curve given by the spectrobolometer a correction factor. The correction factor is equal to the area under the two ends of the curve of spectral radiant flux. With this correction factor the spectrobolometer curve is extended to the whole range of the pyrheliometer, and the area under the curve is equated to the pyrheliometric reading.

Thus the relative scale of the spectrobolometer is converted to an absolute scale and values of spectral radiant flux in watts cm^{-2} are available for the range 0.346 to 2.4 μ.

These values, however, refer to the solar energy received at the surface of the earth. The table of values thus obtained for different wavelengths are next extrapolated to zero air mass by comparing the data for different zenith angles. For large zenith angles the assumption that the optical air mass, m, is equal to the secant of the zenith angle does not hold good, and the modifications given by Bemporad[15] for the curvature of the atmosphere and refraction are to be applied.

The extrapolation to zero air mass gives the curve for spectral radiant flux in the range 0.346 to 2.4 μ outside the earth's atmosphere. The area under the curve is determined by integration. To the integrated value is added the zero-air mass corrections, namely, the areas under the curve of solar spectral radiant flux in the ultraviolet range below 0.346 μ and in the infrared beyond 2.4 μ . The final result of this procedure is the solar constant.

The Smithsonian procedure has remained practically the same over the years, but the value of the solar constant has often been revised partly due to improvements in methods of measurements and data reduction and partly due to revision of the pyrheliometric scale.

2. Parry Moon's Analysis

A contribution of major importance in our current knowledge of the solar radiant flux was made by Parry Moon in 1940. Moon's main purpose was to propose standard solar radiation curves for engineering use. He attempted to collate and compare available data on questions such as variation of solar illumination with seasons of the year, hours of the day, latitude of location, height above sea level, etc. In doing so, he made a systematic study of the absorption effect of the atmosphere and the spectral distribution of radiant flux outside the atmosphere.

Parry Moon made a detailed analysis of the absorption effects of the atmosphere. The results are presented in a series of tables and graphs which it is not necessary to reproduce here. The main results are summarized in figure 2, reproduced from P. R. Gast, which gives four curves related to solar spectral radiant flux. The lowest curve which has a large number of sharp dips is the spectral radiant flux as observed by a ground - based instrument when viewing solar radiation at zenith angle zero, that is, when the path of sunlight is normal to the earth's surface.

The smoother curve shown above the experimentally observed curve is what the spectral distribution would be in the absence of the major molecular absorption effects of O_2, O_3, H_2O and CO_2.

The third curve is the solar spectral radiant flux for air mass zero. This curve, however, is based not on Moon's computation, but on the later and more accurate revision of Smithsonian data given by Johnson. A fourth curve, the blackbody radiation curve for 6000°K, is shown for purposes of comparison.

Another major contribution by Moon was a comparison of the Smithsonian results with those of other independent observers. This is shown in figure 3. Smithsonian's best results are believed to be the weighted average of the measurements of 1920 - 22, which is shown in the figure by circles, and the circles are joined together by a short dash curve. Three other sets of Smithsonian data shown in the figure are from earlier periods: 1903 - 1910, 1903 - 1910 omitting quartz results, and 1916 - 1918. These results are compared with those from three other independent sources, Wilsing's measurements made at Potsdam[16], Pettit's measurements[17] and those of Fabry and Buisson[18]. The data of figure 5 are in arbitrary units, on a log-log scale, and hence the shape of the curves appears different from those of figure 2. The log scale for spectral radiant flux permits one to shift any set of points up or down to secure maximum agreement with all the other sets. The blackbody distribution shown in figure 3 by long dash curve is for 6000°K; this temperature was chosen because the maximum of the 6000°K blackbody distribution occurs at about the same wavelength as for the Smithsonian 1920 - 22 results. The standard curve which Moon proposed as the best fit after due weighting for all published results is shown by the heavy continuous curve.

Moon's proposed curve follows the data of Fabry and Buisson in the wavelength range below 0.32 μ and the data of Pettit for the range 0.32 μ to 0.40 μ. He considered these more reliable for the respective ranges. The Smithsonian values were apparently too high because of scattered light in the spectrograph. In the range 0.40 to 0.60 μ the Smithsonian results are in general agreement with other results. Moon's curve departs again from the Smithsonian results in the longer wavelength range. In the range 0.60 to 0.75 μ the Smithsonian values are lower than all the other values which are in close agreement.

For the range 0.50 to 1.0 μ the depression of the solar curve below the 6000°K blackbody curve is so well established experimentally that Moon felt there is no justification in following the Planckian curve in this range. In the infrared, beyond 1.25 μ up to 2.5 μ, the 6000°K Planckian curve seemed sufficiently close to all available experimental data other than the Smithsonian 1920 - 22 data. In the range beyond 2.5 μ experimental data are scarce. Water vapor and carbon dioxide have strong absorption bands in this range, so that the extrapolation of ground - based measurements to zero air mass is subject to large errors. Hence Moon suggested the 6000°K Planckian curve for the range beyond 1.25 μ.

The total area under the solar spectral distribution curve proposed by Parry Moon is 0.1322 watts cm^{-2} or 1.896 cal cm^{-2} min^{-1}. The value is based on the 1913 Smithsonian scale and hence must be increased by 2 per cent to agree with the International Pyrheliometric scale 1956. In order to compare Moon's results with the more widely accepted Johnson's results, all values on Moon's scale should
1.026 be multiplied by 1.026 which is the ratio of Johnson's and Moon's values of the integrated solar radiant flux in the wavelength range of Moon's table, that is, for λ greater than 0.29 μ.

3. National Bureau of Standards, Stair and Johnston

Ralph Stair and Russell G. Johnston made in 1955, and earlier years a series of extensive measurements of the spectral radiant flux of the sun. They attempted to eliminate some of the major sources of error of the Smithsonian data.

The authors observe that in the Smithsonian work the solar beam was reflected into a spectrobolometer by a metal coated mirror whose reflectivity was subject to change with age. The light is incident on the mirror at different angles, which introduces another factor of uncertainty in the reflection coefficient of the mirror. The solar image is focussed on the slit of the spectrograph, and hence the spectrograph views only a very small portion of the solar disc at a given time. Large and rather uncertain correction factors are involved in attempting to calculate the energy of whole solar disc from such measurements.

Another source of error in the Smithsonian data is that a pyrheliometer is used to integrate the energy of the whole spectrum and to obtain the result in absolute units. This involves several assumptions based on inadequate observational data concerning the absorption of energy by the atmosphere and the spectral limit of the pyrheliometer.

Stair and Johnston adopted an experimental arrangement which eliminated automatically several of these sources of error. The apparatus was set up at a location where the effects of the atmospheric absorption were considerably less than at sea level in a densely populated city. The location chosen was Sunpot, New Mexico, at an altitude of 9200 feet. The spectrum was scanned by a Leiss double quartz prism spectrograph. It was mounted on the polar axis and driven across the sky. Hence the corrections for oblique incidence of light on heliostat mirrors could be eliminated. A specially designed amplifier circuit ensured a high degree of linearity of response. Tungsten ribbon standard lamps calibrated at the National Bureau of Standards were used to reduce the readings to absolute intensity values.

Measurements were made on four days, June 3, 4, 6, and 7, 1955, in the spectral range 0.3 to 0.54 microns. On four other days, June 16, 17, 18 and 19, measurements were made in the range 0.32 to 2.6 microns. The effect of atmospheric attenuation was determined by the conventional method of assuming that the pathlength through the atmosphere is proportional to the secant of the zenith angle. A complete discussion of the methods of data reduction are given in various publications of Stair and his coworkers[19, 20, 21, 6].

The solar constant is calculated from the area under the spectral radiant flux curve for zero air mass. The experimental curve is for the actual sun - earth distance at the time of the measurement. In order to get the values of spectral radiant flux for the average sun - earth distance the observed values were multiplied by 1.0244. No data for the spectral radiant flux are experimentally available for the ultraviolet range below $0.3\,\mu$ or for the infrared range above $2.6\,\mu$. For the ultraviolet, the curve is arbitrarily assumed to drop down to zero at about 0.2 or $0.22\,\mu$. A correction factor of 0.06 calories per sq. cm. per minute is assumed to be the probable solar energy of wavelength beyond $2.5\,\mu$, based on a blackbody curve at the solar temperature. With the addition of these correction factors, the value of the solar constant is 2.05 calories per sq. cm. per minute.

According to the authors this value is probably correct to less than 5 percent, and "is in general agreement with recent estimates, being a little higher than those usually reported by the Smithsonian Institution." Johnson's value is 2.00 cal cm^{-2} min^{-1} which is only 2.5 percent less than Stair's value, and hence well within the percentage accuracy claimed by Stair. The infrared correction of 0.06 cal cm^{-2} min^{-1} assumed by Stair is 2.93 percent of the total, and is slightly below Johnson's estimate for this range, which is 0.065 cal cm^{-2} min^{-1} or 3.27 per cent of the total.

In their discussion of the data, Stair and Johnston stress the complicated nature of the steps involved in gathering and evaluating the measurements. There are numerous sources of uncertainty and error. Hence the accuracy cannot claim to be better than plus or minus a few percent. They also observe that the results they obtained at Sunspot were slightly different from those they had reported earlier from their measurements at Climax[20] and at Sacramento Peak[21]. This is probably to be attributed to improvements in the experimental technique, or may also be due to solar changes within the interval. Another important source of uncertainty which the authors have stressed is the radiometric standard. The values currently adopted for the spectral emissivity of tungsten are subject to revision, and such revision, if later found necessary, will alter the values of the solar constant and the solar spectral radiant flux.

4. Naval Research Laboratory, Dunkelman and Scolnik

Another set of measurements which should be reviewed in some detail were made by Dunkelman and Scolnik. These measurements were made in 1951, but were not reported in detail until eight years later in 1959[2]. The conventional method used by Stair, Moon and earlier workers was adopted to extrapolate from ground-based measurements to zero air mass. The observation station was situated on the top of a flat rock, at an elevation of 8025 feet, on Mount Lemmon, near Tucson, Arizona. But it was a real disappointment to the observers that the sky above Mt. Lemmon was overcast with clouds during most of the period, September 20 to October 17, 1951, which they spent on the mountaintop. Useable data were obtained only on one day, October 4. On that day a total of 25 spectral scans were made at different times from early morning till late in the evening.

The spectrum was produced and the energy scanned by means of Leiss quartz double monochromator, detected by a 1 P 2 1 photomultiplier tube, amplified and presented on a strip chart recorder. The wavelength covered was from 0.303 μ to 0.700 μ, the only range where the 1 P 2 1 detector is sufficiently sensitive. In this small range, wavelengthwise only 6 per cent of the entire range of 0 to 5 μ of the solar spectrum is contained about 40 per cent of the total solar energy. The purpose of the observers was not to chart the entire spectrum or to evaluate the solar constant, but to provide a calibration standard whereby the relative measurements of the rocket data collected by the Naval Research Laboratory in the little known ultraviolet range could be reduced to absolute values of radiant energy.

The equipment was calibrated frequently by using the spectrum of the tungsten lamp. The tungsten lamp which operated at a temperature of 2800°K had previously been calibrated at the National Bureau of Standards with reference to a blackbody, in accordance with the Bureau's well established procedure. There is no reason to doubt the N. B. S. calibration technique, and it was decidedly the best available at that time. However it should be noted that the N. B. S. does not claim an accuracy better than 5 per cent for its calibration table. The method which was used in 1951 involved a series of difficult calculations from the color temperature to the true temperature, and thence through blackbody radiation functions and spectral emissivity curves of tungsten to the spectral radiance of the tungsten ribbon as viewed through a quartz window. This method has since been replaced, and the present calibration tables give the spectral radiance at selected wavelengths for a specified current.

The block diagram of the apparatus used by Dunkelman and Scolnik is reproduced in figure 4 from their original paper[2]. Light from the sun or from the standard source, L, is introduced into the Leiss double monochromator from the magnesium carbonate block C. The lamp current and the voltage are monitored continously by means of a voltmeter V and ammeter A, and adjusted when necessary by a variac VA. The mirror M_L is interposed in the path of the beam from the siderostat when a calibration run is to be made. The signals from the photomultiplier PM are amplified by a D. C. amplifier and recorded on a stripchart recorder. A bucking box B serves to subtract the dark current.

A major contribution of Dunkelman and Scolnik was the detailed comparative study they made of the data obtained by different observers. The results of this study are presented in figures 5 and 6, also reproduced here from their original paper.

In figure 5 are given the better known measurements of the entire solar disc made prior to 1949. The Smithsonian data[22,23] are usually shown in relative units only, though they are basically absolute. Pettit[24] normalized his spectral solar radiance data to agree with those of the Smithsonian at 0.45 μ. In figure 5 both the Smithsonian and Pettit's curves have been readjusted downwards to make them conform to the new absolute energy values for the solar spectrum given in the Ninth Revised Edition of the Smithsonian Physical Tables[25]. The short curve for the range 0.3 to 0.33 μ is based on Stair's absolute measurements of 1947[26]. The data of Hess[27], Reiner[28], and Gotz and Schonmann[29] were published only on a relative scale. Dunkelman and Scolnik normalized these curves against Pettit's at 0.4725 μ in order to make a meaningful comparison. The large differences in the wavelength range below 0.4 μ are probably due to stray light in the spectrograph, uncertainties in the calibration of the tungsten standard, and errors in the extrapolation to zero air mass in a wavelength range of high absorption.

In figure 6 is shown a comparison of Dunkelman and Scolnik's measurements with more recent data, those of Pettit and of Stair and Johnston. The curves are based on integrated energy values and do not show the fine details of figure 5. Stair and Johnston's curve agrees closely with that of Dunkelman and Scolnik in the wavelength range below 0.5 μ, whereas Pettit's values are lower by about 25 per cent. In the range above 0.5 μ, the results of Stair and Johnston are high, whereas those of Dunkelman and Scolnik and of Pettit are in fairly close agreement. Solar spectral radiant flux at 0.6 μ is 1.81 μw cm^{-2} A^{-1} according to Dunkelman and Scolnik and 1.963 μw cm^{-2} A^{-1} according to Stair and Johnston. Francis Johnson had concluded that the original scale of Dunkelman and Scolnik had to be raised by 9 per cent in order to conform to the Smithsonian data and the NRL rocket data. The value 1.81 is on this raised scale. The value on the original scale is 1.66 μw cm^{-2} A^{-1} which is different from Stair's value by 18.2 per cent. This large difference occurs in a wavelength range which might be considered the most favorable for accurate solar measurement, a range where the solar energy is high, atmospheric absorption is low, detectors are highly sensitive and the tungsten standard is sufficiently strong. Concerning this difference, however, Dunkelman and Scolnik[2] make the following observation: "The results of Stair between 5000 and 7000 A are high, and are not in agreement with any previous work including his own earlier measurements. Further more they lead to a value of extra - terrestrial illuminance that is higher than recent measurement of Karandikar[30], and most previous solar illuminance measurements."

5. Revision of Smithsonian data by Francis S. Johnson

Francis S. Johnson and his coworkers at the Naval Research Laboratory undertook a major revision of the solar constant and of the solar spectral radiant flux. This work was stimulated by the new measurements in the range 0.22 to 0.34 μ made by rocket-borne spectrographs[31,32] and by the Mount Lemmon data of Dunkelman and Scolnik. Johnson's discussion of this revision was reported in 1954 in the Journal of Meteorology[1]. In 1957 an abridged report was published by R. Tousey in Nuovo Cimento[14]. Johnson's revision started from the measurements which had been made for over half a century by the Smithsonian Institution. A number of corrections are involved in deriving the solar constant from the Smithsonian data, and Johnson attempted to reevaluate these corrections with the aid of the more recent NRL data.

The starting point for Johnson's revision was the Smithsonian value 1.934 cal cm^{-2} min^{-1}, which is on the so-called "true" scale. Subtracting from this the Smithsonian zero air mass correction of 0.061 in the UV below 0.346 μ and 0.038 in the IR above 2.4 μ, Johnson obtained 1.835 cal cm^{-2} min^{-1} as the radiant flux for zero air mass in the range 0.346 to 2.4 μ. To this value Johnson added three correction factors, 0.006 an increase due to the revised UV spectrobolometer correction based on Mt. Lemmon data, 0.085 the revised UV zero air mass correction based on NRL rocket data and Mt. Lemmon data, and 0.076 the revised IR zero air mass correction based on the assumption that in the IR from 2.4 to at least 14 μ, the solar spectral radiant flux for zero air mass is that of a 6000° K blackbody. This assumption had been made earlier by P. Moon, and was apparently justified by the work by A. Adel[33,34] and R. Peyturaux[35]. These three corrections when added to 1.835 yield the final value of the solar constant 2.002 cal cm^{-2} min^{-1}. Tousey[14] observes: "We prefer to call it 2.00 since we feel that the probable error may be of the order of $\pm$ 2 percent." Thus we have the value most frequently cited in literature, 2.00 cal cm^{-2} min^{-1}, and refered to as the NRL value or the Johnson value.

Johnson's revision of the Smithsonian data also yielded a new table for the solar spectral radiant flux. The starting point is a curve of the spectral radiant flux on a relative scale, the same as for the solar constant. This curve is based on three sources which Johnson considered the most reliable, the NRL rocket data for wavelengths shorter than 0.318 μ, the Mount Lemmon data for the range 0.318 to 0.60 μ and Parry Moon's results for the wavelength range beyond 0.60 μ. The normalization procedure for converting the relative scale to an absolute scale is based on the reevaluation of the spectrobologram corrections and the zero air mass corrections. Johnson[1] has discussed in detail the steps involved in the procedure.

Johnson's data on solar spectral radiant flux is given in table I. It is reproduced from a more recent publication edited by Johnson, Satellite Environment Handbook[36]. The same data re also presented in figure 7, which shows some of the finer details which are usually omitted in reproductions of the Johnson curve. Figure 7 is a reduced photograph of a drawing made on large scale graph paper of all the data points of table 7.

IV. CONCLUSION

In view of the discussions in the previous sections, it would seem highly desirable that a new attempt be made to obtain more accurate and complete experimental data on the solar constant and the spectral distribution of the solar radiant flux. Johnson's work was mainly one of revision, and the experimental data for the revision had been obtained many years earlier by the Smithsonian Institution. The observations of Dunkelman and Scolnik were made on one single day, and were limited to the visible portion of the spectrum. The data of Stair and Johnston were averaged over eight days, but the authors themselves emphasize the large uncertainties inherent in the method.

The task of accumulating new experimental data with a degree of accuracy considerably superior to that of currently available data, will necessarily be a huge one. The justification for attempting such a task lies mainly in the importance of the solar constant in many areas of physics and engineering. The thermal balance of the earth depends on the energy from the sun. The attenuation characteristics of the atmosphere remain uncertain because the energy received above the atmosphere is uncertain. The solar radiant flux is an important parameter in most problems of astrophysics and solar physics. It is indeed a disturbing situation that so important a physical constant has an uncertainty of a few parts in a hundred, when standard tables of the physical constant, such as the velocity of light, electron charge, Planck's constant, etc., quote the values with an accuracy of one part in a million or a billion.

The uncertainty in the solar constant and the solar spectral radiant flux has serious consequences for solar simulation and the thermal balance of spacecraft. This aspect of the question has a special interest for those engaged in building and testing satellites, since one of the more accurate methods of improving upon current data is to make measurements from above the atmosphere by satellite-borne instruments. The information which the satellites need for ensuring their operational stability can best be obtained by the satellites themselves. We have discussed earlier to what extent errors in the solar constant and the solar spectral radiant flux would affect the equilibrium temperature of spacecraft. A vast amount of effort is now being made in building and maintaining solar simulators for pre-launch testing of satellites and space probes. The operational assumption in such testing is that if the satellite fails to maintain the required thermal balance under the simulated conditions it will also fail to do so under actual conditions. High energy radiant sources, as for example, the carbon arc or the mercury-xenon arc, illuminate the test floor with energy which matches, as far as practicable, the energy of the sun both in spectral distribution and in total energy. It is obviously impossible to simulate accurately something unknown or uncertain. However, it should be pointed out that at the present time the degree of error in our knowledge of the solar energy is not the only obstacle or the major obstacle for adequate solar simulation. The margin of tolerance permitted or realistically attainable with high energy solar simulator sources is larger than the assumed margin of error in the published values of the solar constant and the spectral distribution of solar radiant flux. However, as efforts are being made to improve the energy output and the spectral characteristics of solar simulators, a parallel effort should be made to ascertain more accurately what one is trying to simulate. The large uncertainties in the ultraviolet region, referred to by P. R. Gast, may also have unpredictable effects on the rapid deterioration of certain surface materials.

R. Tousey[14] concluded his discussion of the NRL revision of the solar constant with this remark: "I feel that new work on the solar constant is in order, but it will not be easy to improve on the accuracy attained by the Smithsonian. Attempts to make measurements directly from rockets have been made, but not yet with completely satisfactory results. The values obtained were of the order of 2.0 however. Measurements from the ground could now be made with increased accuracy due to the present day availability of many new radiation measuring techniques. To do this will require a long series of painstaking measurements, preferably, from two independent stations located at widely separated points on the earth."

Tousey's observations were made in 1957 at the threshold of the satellite age. The intervening years have witnessed a rapid progress in satellite technology. Satellites of the near future give promise of larger and bolder experiments.

The severe limitations which existed in earlier years on the size and mass of the experimental package and on the available supply of power are now being removed. The obvious advantage of a satellite experiment to measure the solar spectral radiant flux is that the spectrograph is outside the earth's atmosphere and that the difficult and highly doubtful corrections for atmospheric absorption are unnecessary. Measurements can be made over a prolonged period of time, and many repeated values can be taken so as to average out all random experimental errors.

However, every precaution should be taken to forestall systematic errors which might wholly vitiate the results. The measurements of the Smithsonian, N.B.S. and N.R.L. were made by experienced observers who always had ready access to the apparatus and could make readjustments whenever necessary. A completely automated experimental package presents problems of a different order of magnitude. But the solutions to these problems are within reach for present day satellite technology.

A quartz double prism monochromator might well be the main unit in the experimental package. More than one energy sensing device will be needed to cover completely all ranges of wavelength. Some form of 'on-board' calibration, as for example, with a secondary standard of spectral radiance, will be necessary. Adequate shielding should be provided for stray radiation from the earth or from the body of the satellite itself; or these will have to be corrected for. The satellite should have the attitude control for pointing constantly to the sun, and the optical system should be such as to view the whole solar disc.

A total energy sensor might well be needed as an auxiliary piece of apparatus. R. Hanel[37] and his coworkers have suggested a compact unit of this type, and the original design is now being improved upon. Readings of the total energy sensor would provide an additional means of calibration, in the same manner as the Smithsonian pyrheliometer was used to convert the relative scale of the spectrobolometer to an absolute scale.

Due attention will have to be paid also to small percentage of energy in the ultraviolet and the infrared wavelength ranges where the quartz prism is an effective absorber. The N.R.L. rocket-borne spectrographs and the albedo measuring devices of the Tiros satellites provide many helpful suggestions for mapping accurately these relatively inaccessible regions of the spectrum.

The prism spectrograph with the auxiliary units for calibration provides one method of approach and perhaps the best. A slightly different method is to employ a series of narrow-band-pass filters. Many different types of filters are commercially available. The relative ruggedness and simplicity of an experimental package with a series of filters and a thermopile might more than compensate for the lack of detailed spectral resolution. But considerable research still needs to be done on the stability of the transmission characteristics of the filters and on the method for obtaining a curve for the spectral radiant flux from the energy transmitted by the filters.

Richard Tousey[14] justly pointed out the desirability of more ground-based measurements, since new radiation measuring techniques are now available. He also said that measurements should preferably be made from widely separated points on the earth. More ground-based measurements are undoubtedly of great value.

One objection to ground-based measurements is that they would tell us more about the characteristics of the atmosphere than about the solar radiant flux. Abundant data about the upper atmosphere and about the earth albedo are now available from satellite experiments. These data might well serve for a more reliable extrapolation to zero air mass than was previously possible. The problem of extrapolation can be considerably reduced if the measurements are made not from a mountain top but from a high flying aircraft such as the X-15, A-11 or U-2 or from a balloon. These provide an alternate approach to the satellite experiment.

A major problem in all absolute measurement of energy is the standard of spectral radiance and total radiant flux. Data of any degree of accuracy which are cited in literature, whether of Smithsonian, N.R.L. or N.B.S., refer ultimately to the spectral radiance standards of the N.B.S., or to the Smithsonian pyrheliometer. There is no complete agreement between different countries and different national laboratories concerning the standard of energy. If a determined and massive effort is made to reevaluate the solar constant and the solar spectral radiant flux, an essential part of that effort will be to define an internationally acceptable standard of energy.

V. ACKNOWLEDGMENTS

This study was prompted partly by a conference on Solar Simulation Research and Technology, held on February 27-28, 1963, at the Headquarters of the National Aeronautics and Space Administration, Washington, D. C. Several of the panelists raised questions regarding the reliability and degree of accuracy of our current knowledge of the solar constant and of the solar spectral radiant flux which the space environment simulators are trying to match. The author wishes to thank the members of the panel and in particular Conrad P. Mook of the Office of Advanced Research and Technology, NASA, the moderator of the Conference, for several helpful suggestions. The author is particularly indebted to Dwight C. Kennard, Technical Assistant for Advanced Research and Technology, Test and Evaluation Division, Goddard Space Flight Center, NASA. His keen interest in this study, the constant encouragement and many helpful discussions, and the items of information which he gathered from different sources about the feasibility of further measurements were a major factor towards the completion of this work. Thanks are due to two other members of the T & E Division, GSFC, Elias Klein, Director of the Summer Workshop, and Henry Maurer, Jr., Head, Thermodynamics Branch. Brief discussions which the author had with Richard Tousey, Ralph Stair and Lawrence Dunkelman proved highly beneficial; all three have made rich contributions to this field; their help is gratefully acknowledged.

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Captions for Figures

Caption for Tables

Contents

FIGURE I

FLOW CHART OF SMITHSONIAN PROCEDURE

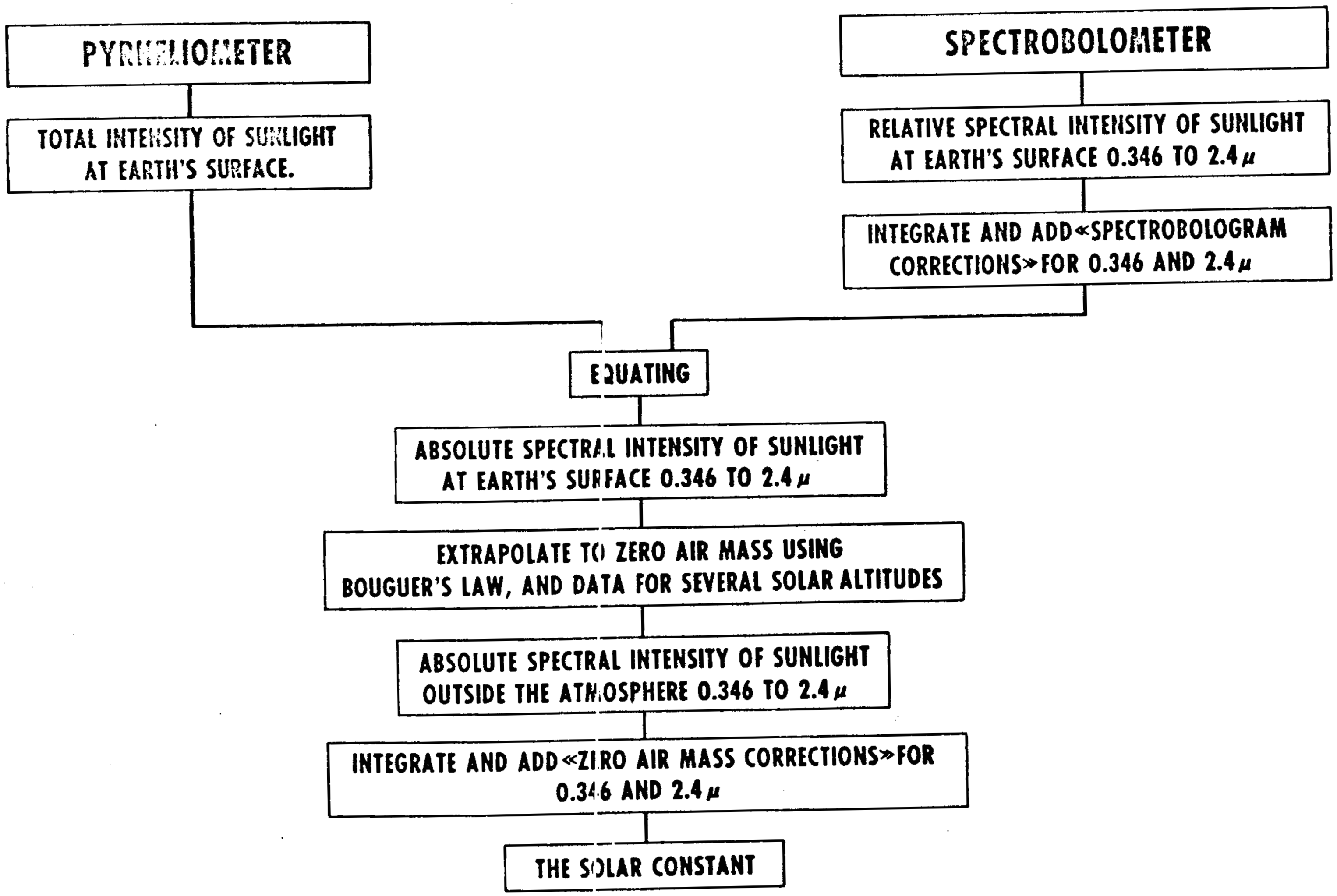

FIGURE 2

CURVES RELATED TO SOLAR ENERGY

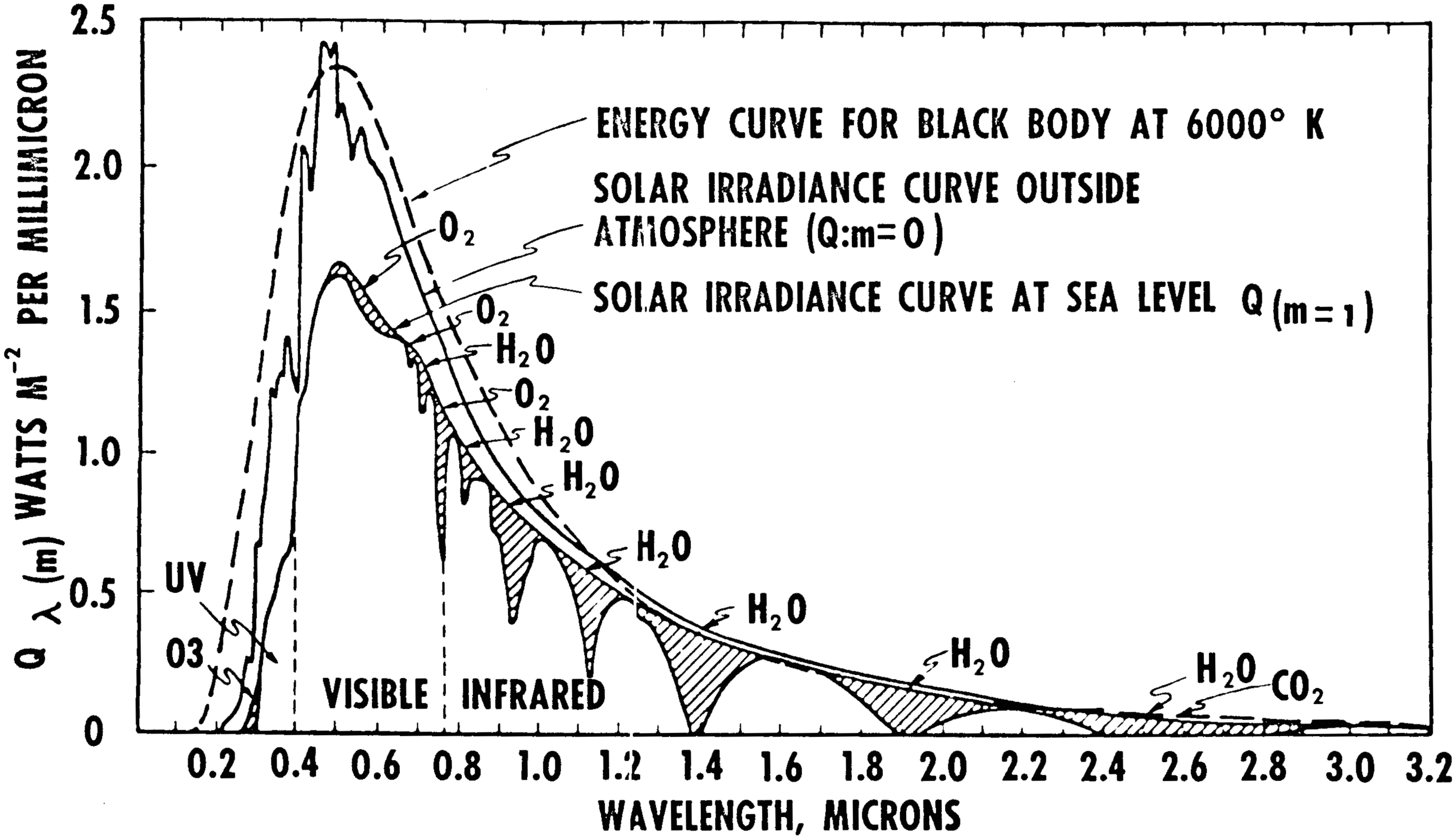

FIGURE 3

PARRY MOON'S CURVE

SOLAR IRRADIATION ON A SURFACE OUTSIDE THE ATMOSPHERE.

- ▽ FABRY & BUISSON
- ⌀ PETTIT
- ○ WILSING
- △ 1903-1910
- x 1903-1910 (OMITTING QUARTZ RESULTS)
- □ 1916-1918
- o--o 1920-1922
- –– BLACKBODY, 6000° K.
- — PROPOSED STANDARD CURVE

SMITHSONIAN INSTITUTION

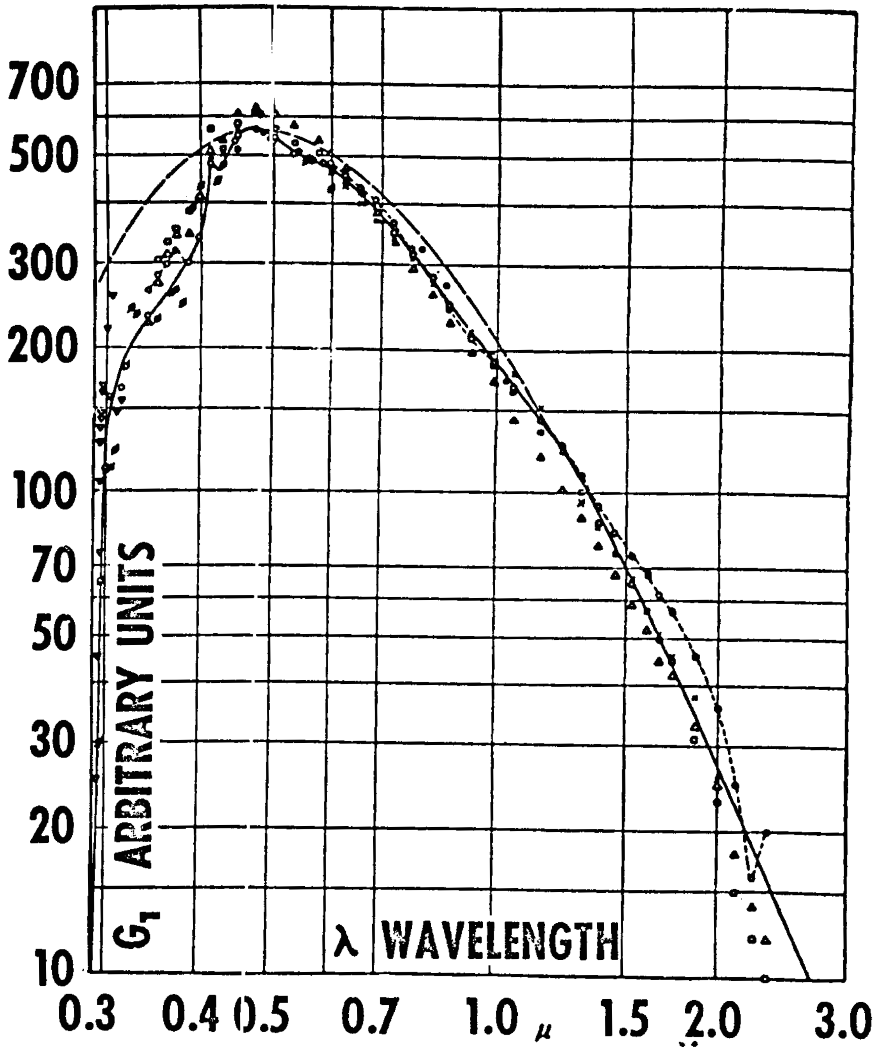

FIGURE 4

BLOCK DIAGRAM OF APPARATUS

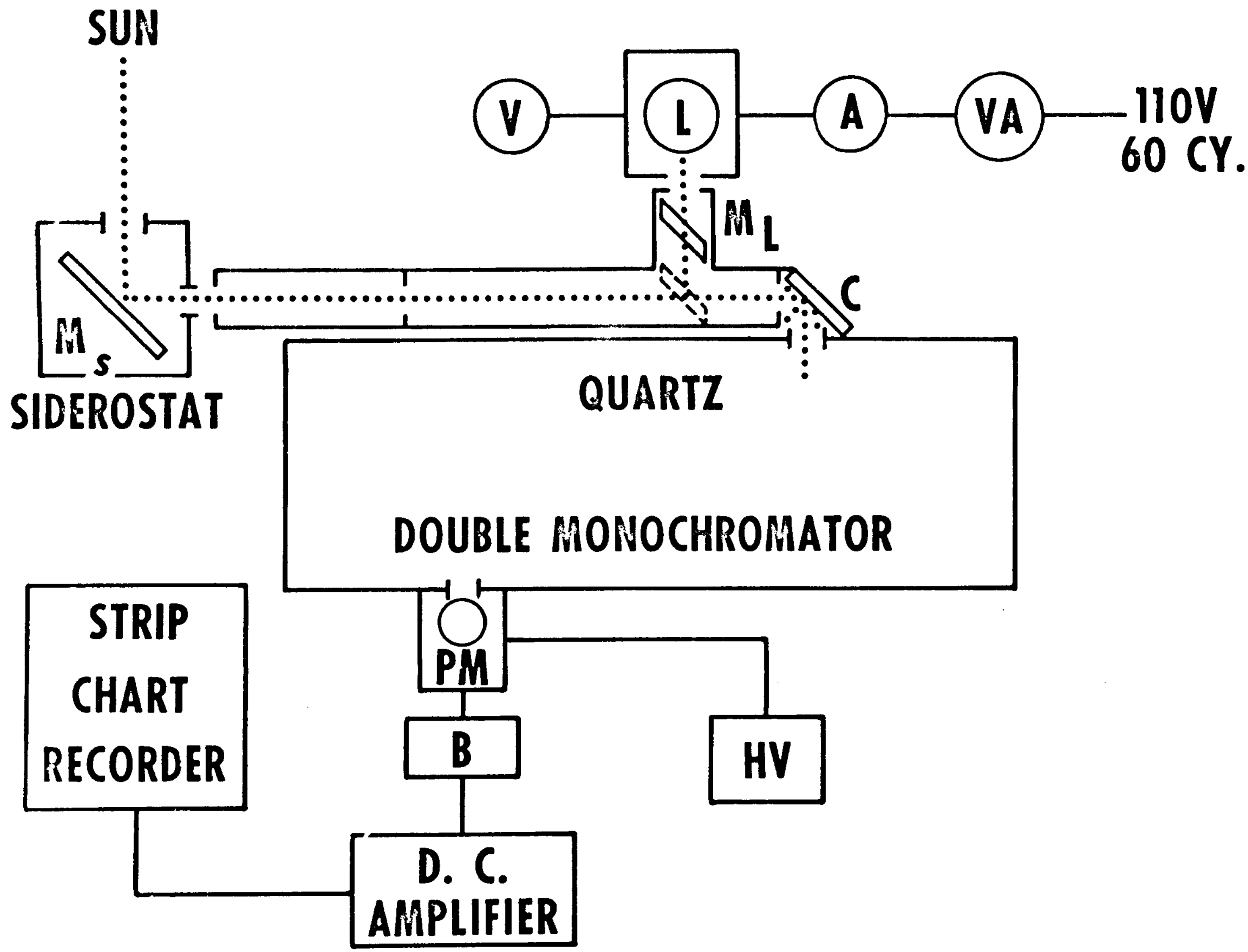

FIGURE 5

DATA PRIOR TO 1949

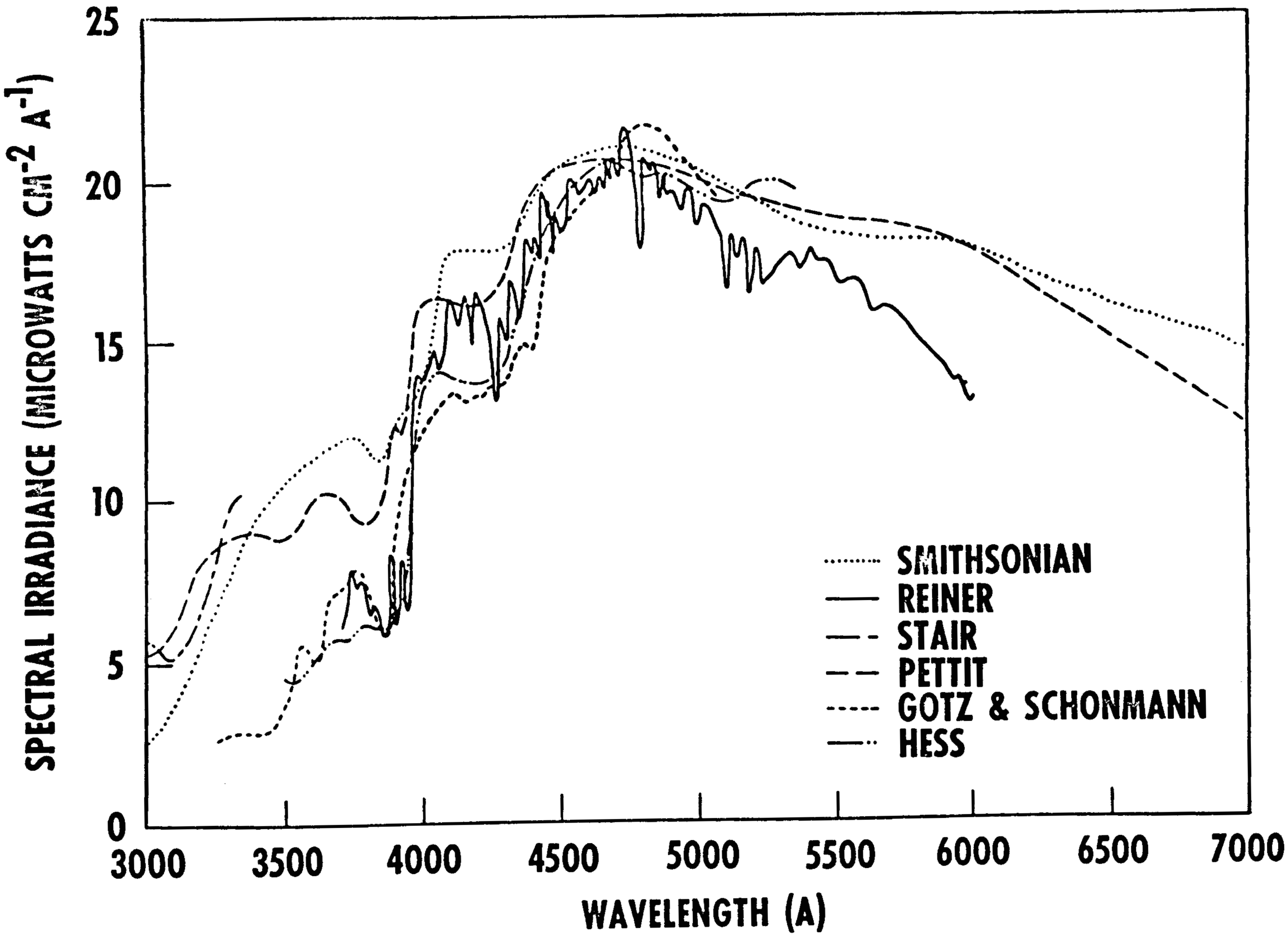

FIGURE 6

DATA OF NRL PETTIT AND STAIR

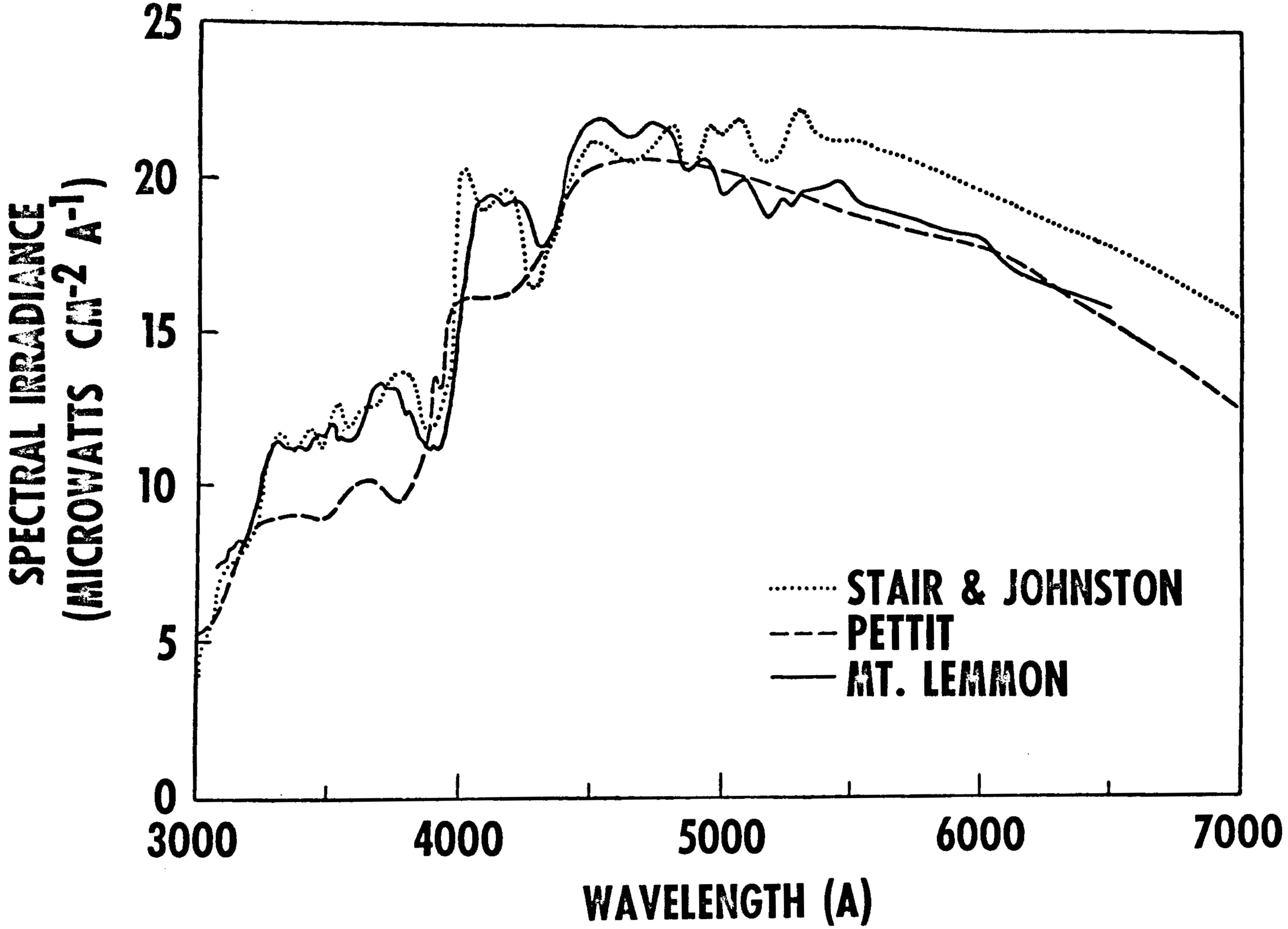

FIGURE 7

THE JOHNSON CURVE