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**A Correlation Between Spectral Class and
Spectral Irradiance Using Planck's Blackbody Radiation**

**A Thesis
Presented for the
Master of Science
Degree
The University Of Tennessee, Knoxville**

Valinda Dee Kirkland

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Abstract

Stars may be used as calibration sources for sensors. This may be accomplished by a method that approximates the spectral irradiance of a star. This method distributes the total irradiance of a star as a blackbody function with an effective temperature.

The results were compared with measured data. The accuracy of the method varied with the spectral class and luminosity type of a star. It also varied with the spectral range being considered. It was concluded that this method was a good first order approximation to the spectral irradiance of a star in the visual and infrared spectral regions but not in the ultraviolet spectral region.

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List of Symbols

M_λ	Spectral Radiant Energy
$M_{\lambda_1-\lambda_2}$	Radiant Energy between λ_1 and λ_2
M	Total Radiant Energy
c	Speed of Light
h	Planck's constant
k	Boltzmann's constant
ν	Frequency
λ	Wavelength
σ	Stefan-Boltzmann constant
m_1, m_2	Magnitude of stars
m_{bol}	Apparent bolometric magnitude
m_v	Apparent visual magnitude
BC	Bolometric Correction
f_1, f_2	Fluxes of stars
E	Total irradiance of a star
bw	bandwidth
E_λ	Spectral irradiance of a star outside the atmosphere of the Earth
T	Temperature
T_e	Effective temperature
H	Hydrogen
He	Helium
N	Nitrogen
O	Oxygen

Chapter 1

Introduction

In many spectroscopic investigations, the instrument must be calibrated to obtain absolute unit data. This calibration has proved difficult for the instruments aboard satellite or aircraft platforms. Fortunately, the recorded data many times include not only the test subject but also the stellar background. The stellar sources are used as calibration sources.

In order to use the stars as calibration sources, the spectral irradiance of a star must be determined. Unfortunately, very few data are available for most stars, beyond their astronomical identification and classification. This classification entails the magnitude, spectral class and luminosity type of a star. With this classification, a spectral irradiance-magnitude relation can be used to find the spectral irradiance of a star.

The spectral irradiance-magnitude relation is a correlation between the spectral class of a star and its spectral irradiance. With this relation, a spectral irradiance equation can be developed based on the Planck blackbody radiation law and the assumption that stars are blackbodies.

The purpose of this thesis is to discuss the theory and assessment of the spectral irradiance equation. The validity of the assumption that stars radiate as blackbodies will be examined and the limits of its application to star classes and

types will be identified.

In chapter 2, radiometric quantities, blackbody radiation, and classification of stars will be reviewed. Chapter 3 contains the explanation of the theory of the spectral irradiance equation. The verification of the equation will be discussed in chapter 4. Finally, chapter 5 ends this thesis with a discussion of the sources of errors and the summary.

Chapter 2

Review

Radiometric Quantities

Radiometry is the measurement of radiant energy in the electromagnetic spectrum. The optical spectrum is useful for studying test subjects in orbit and encompasses ultraviolet, visible, and infrared radiation. It is called the optical spectrum because the radiation within these wavelengths behaves according to the law and principles of optics and is measured by optical instruments and techniques (Stimson, 1974, p.1). The optical wavelengths are associated with the spectral properties of an object (Grum, 1979, p. 30). Radiometry includes the division of photometry, which deals with the visual radiation (Wyatt, 1978, p.9-16).

Radiometric quantities of interest are radiant power, spectral radiance, spectral irradiance, spectral intensity, spectral exitance, emissivity, reflectivity, absorptivity, and transmissivity. Spectral irradiance is closely associated with the sensor while the other quantities deal with the source. Table 1 gives a brief summary of these quantities along with their symbols and units. While the other quantities are more closely associated with ideal radiometry, the emissivity and transmissivity are associated with applied radiometry (Spiro, 1965, p. 28).

The first spectroradiometric quantity to be reviewed is radiant power. It is the time rate of flow of radiant energy.

Table 1 Radiometric Units

NAME	SYMBOL	DIMENSION	UNITS	
Radiant Power	ϕ	power	Watt	$\phi = dU/dt$ U=Radiant energy
Spectral Intensity	J_λ	$\frac{\text{power}}{\text{solid angle} \cdot \lambda}$	$\frac{\text{Watt}}{\text{sr} \cdot \text{\AA}}$	$J_\lambda = \frac{d\phi}{d\Omega}$
Spectral Radiance	L_λ	$\frac{\text{power}}{\text{area} \cdot \text{solid angle} \cdot \lambda}$	$\frac{\text{Watt}}{\text{cm}^2 \cdot \text{sr} \cdot \text{\AA}}$	$L_\lambda = \frac{d^3\phi}{dA d\Omega d\lambda}$
Spectral Irradiance	E_λ	$\frac{\text{power}}{\text{area} \cdot \lambda}$	$\frac{\text{Watt}}{\text{cm}^2 \cdot \text{\AA}}$	$E_\lambda = \frac{d^2\phi}{dA d\lambda}$
Spectral Exitance	M_λ	$\frac{\text{power}}{\text{area} \cdot \lambda}$	$\frac{\text{Watt}}{\text{cm}^2 \cdot \text{\AA}}$	$M_\lambda = \frac{d^2\phi}{dA d\lambda}$
Emissivity	ϵ	dimensionless		$\epsilon = M_\lambda(\text{source}) / M_\lambda(\text{bb})$
Reflectivity	ρ	dimensionless		$\rho = \frac{\phi(\text{reflected})}{\phi(\text{incident})}$
Absorptivity	a	dimensionless		$a = \frac{\phi(\text{absorbed})}{\phi(\text{incident})}$
Transmissivity	τ	dimensionless		$\tau = \frac{\phi(\text{transmitted})}{\phi(\text{incident})}$

Radiant energy is energy traveling in the form of electromagnetic waves. Radiant power, also called radiant flux, has the units of power (Meyer-Arendt, 1968, pp.2081-2082).

Spectral radiance is the radiant power per unit solid angle per unit area of the source per unit wavelength interval. It is measured in watts per centimeter squared per steradian per angstrom (Wolfe, 1965, pp.4-5). The spectral radiance of a blackbody is calculated by use of Planck's radiation equation if the temperature of the body is known. Blackbodies can be used as spectral radiance standards, and the other radiometric quantities can be derived from spectral radiance (Grum, 1979, p.309). Radiance, which is spectral radiance integrated over all wavelengths, corresponds to photometric brightness, or brightness, in photometric terms. Brightness is the visual response of the observer to an object that is either reflecting or radiating radiation (Stimson, 1974, p.7)

Spectral irradiance is described to be the radiant power incident upon a surface per unit area per unit wavelength interval. It is measured in watts per centimeter squared per angstrom (Wolfe, 1965, pp.4-5). The calibration of a spectroradiometer depends on standards of irradiance at specified distance or spectral radiance which are normally a blackbody radiation sources calibrated by a standard thermocouple or a standard irradiance lamp referred to a

blackbody. The standards can also provide narrow wavelength bands of energy when used with band-pass filters for various test purposes.

Spectral radiant intensity can be calculated from spectral irradiance. It is the product of the irradiance and the distance squared. It has units of watts per steradian per angstrom. It is the quantity most commonly measured (Stimson, 1979, p.263).

Transmittance is defined as the ratio of the transmitted radiation through an absorbing medium to the incident radiation upon that medium. It can be referred to as a property of a medium. Transmittance is a unitless quantity. Transmissivity of an absorbing material is the transmittance of a layer of the medium such that the path of radiant energy is of unit length and the boundary of the medium has no influence.

Spectral exitance, or spectral radiant emittance, is the spectral radiant power emitted by an element of a surface divided by the area of the element. It is measured in watts per centimeter squared per angstrom (Stimson, 1974, p.346).

Spectral exitance can be used to calculate an applied concept called emissivity. Emissivity is a ratio of the exitance of a material source to the exitance of a blackbody source at the same temperature (Spiro, 1965, p.31). The blackbody has an emissivity of one, all other sources have emissivity less than one. A radiating body with an emissivity

that is constant but less than one is known as a greybody. Emissivity is an unitless quantity (Wyatt, 1978, p.36). Figure 1 shows the emissivity and exitance of a blackbody, greybody, and a selective radiator. As can be seen from figure 1a, a blackbody has the highest emissivity possible. In figure 1b, the exitance is shown to be a function of wavelength (Hudson, 1969, pp.40-41).

Reflectivity and absorptivity, in addition to emissivity and transmissivity, are fundamental properties of a material. Both are unitless quantities (Wolfe, 1965, p.8). Reflectivity, which is dependent upon wavelength, is the ratio of the reflected radiant power to the incident radiant power; however, atmospheres are not usually considered to have reflectivity.

Absorptivity is the ratio of absorbed radiant power to the input radiant power. In an atmosphere, the extinction of radiant power is caused by the effects of two mechanisms. The first mechanism, absorption, is the removal of energy from a radiant beam by an atom or molecule. Scattering, the second mechanism, is the change in direction of the radiation out of the field of view of the collecting instrument (Spiro, 1965, pp.30-31).

Blackbody Radiation Theory

A perfect absorber is that which absorbs all incident radiant energy and reflects none. This must be true at all

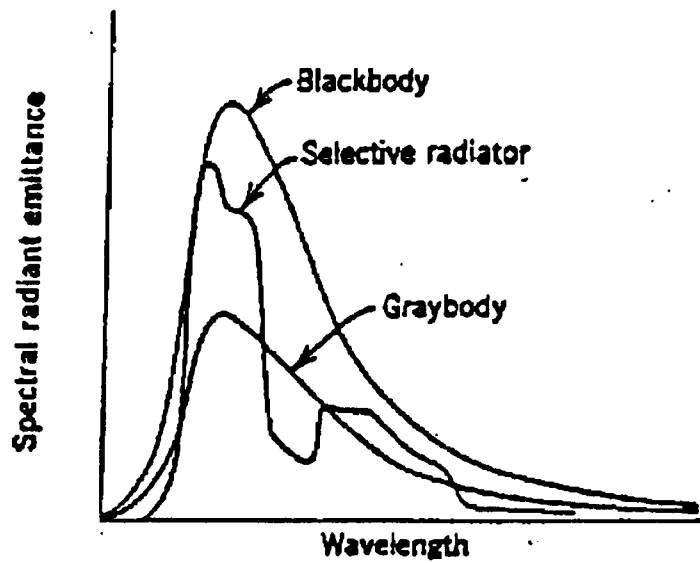
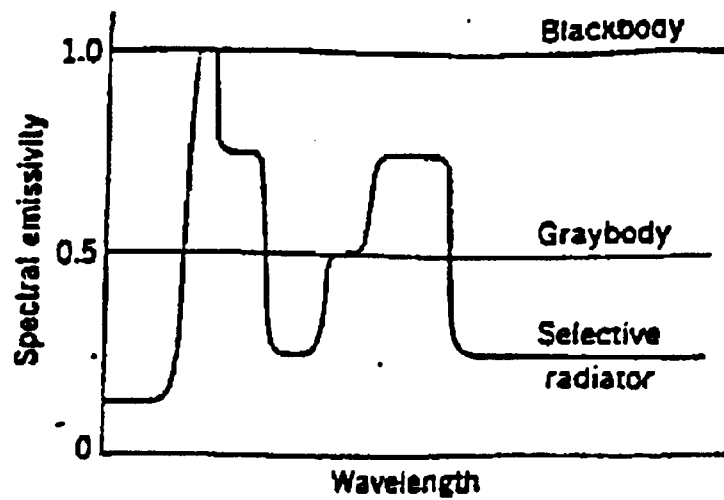


Figure 1 Spectral emissivity and spectral radiant emittance of three types of radiators. a.) Spectral emissivity. b.) Spectral radiant emittance.

wavelengths and at all angles of incidence. A perfect absorber is also known as a blackbody. However, a blackbody is also a perfect emitter. It emits the maximum possible radiant energy at a given temperature. Thus, the emission properties are equal to the absorption properties (Grum, 1979, p.98).

The explanation of the energy distribution of a blackbody provided a major problem to physicists in the second half of the nineteenth century. Wien provided one explanation in his displacement law. This gave the general form of the equation for the distribution; unfortunately, it only agreed with experimental data at short wavelengths and at low temperatures. However, it did provide useful corollaries.

Rayleigh based his explanation on the concepts of classical physics. Thus, his expression fitted the data at long wavelengths and at high temperatures. This expression predicted that as wavelength decreased the energy increased without limit. His expression is now called the Rayleigh-Jeans Law (Hudson, 1969, pp.33-34). Thus, the experimental curve proved incapable of being explained by classical theory. However, in 1900, Planck announced his blackbody radiation theory. He achieved agreement between theory and experiment by quantizing the energies of the oscillators used in classical theory. Each oscillator was assumed to have only discrete energy values. These values differed in energy by $h\nu$.

Planck's radiation law states that the spectral radiant exitance from a blackbody is

$$M_{\lambda} = \frac{2\pi c^2 h}{\lambda^5 (\exp \frac{hc}{\lambda kT} - 1)} \quad (1).$$

This expression is plotted in figure 2 for a temperature of 1600 K. This equation shows excellent agreement with experimental data over a large range of wavelength and temperature. The equations developed by Wien and Rayleigh-Jeans are both approximations to Planck's law, the former in the short wavelength limit and the latter in the long wavelength limit. The constants can be evaluated with the wavelength expressed in angstroms, and the following expression for the spectral exitance is obtained:

$$M_{\lambda} = \frac{3.74 \times 10^{30}}{\lambda^5 (e^{\frac{1.44 \times 10^4}{\lambda T}} - 1)} \quad \text{W cm}^{-2} \text{ \AA}^{-1} \quad (2).$$

By integrating equation 1 over all wavelengths, the total radiation emitted by a blackbody can be found. The resulting equation for exitance is

$$M = \sigma T^4 = 5.67 \times 10^{-12} T^4 \quad \text{W cm}^{-2} \quad (3)$$

is known as Stefan-Boltzmann Law. This agrees with experiment in both the temperature to the fourth power dependence and the constant's value. By differentiating equation 2, the value of λ at which the power is a maximum is obtained for each temperature such that $\lambda T = 289800 \text{ K \AA}$ (Sproull, 1963, pp. 110-112).

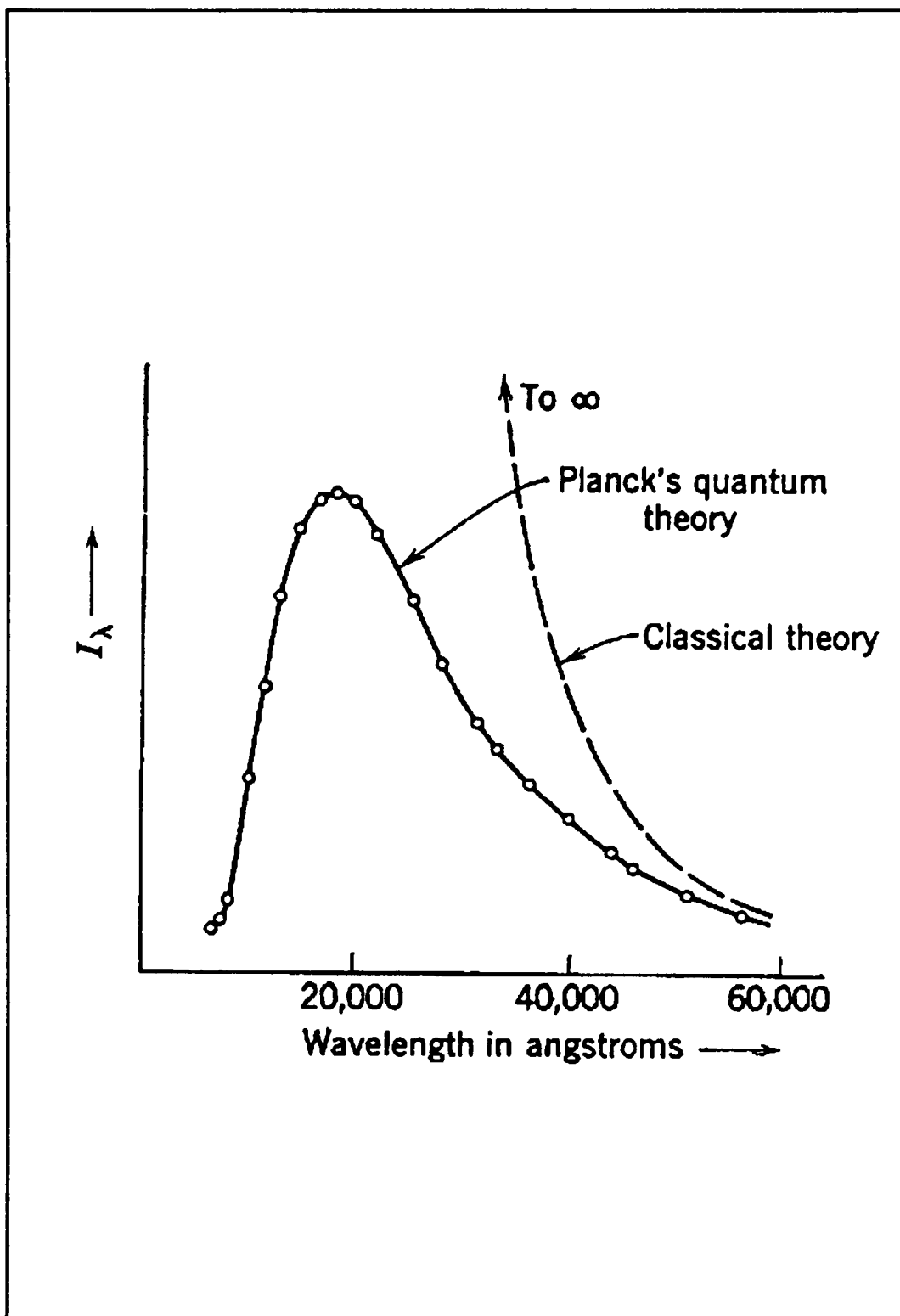


Figure 2 Comparison of classical and quantum theories of blackbody radiation with experiment, $T=1600$ K. The circles are data points. $I_\lambda=M_\lambda$

Classification of Stars

Classifying the stars is a difficult and complex problem. This is mainly due to the numerous cases that are hard to fit into patterns. The classification system, Harvard Classification, has a two parameter code, one of which is the spectrum of the star and the other, the brightness of the star. This system is based on an extensive collection of observed spectra.

This system primarily uses the spectra of stars, which are related to the color of stars; however, the sequence of the system is in terms of decreasing stellar temperature. The spectral classes are denoted by alphabetical letters. Thus, the label O is for the bluest and hottest common stars. The sequence continues through six classes to the reddest and coolest star class labeled M. Table 2 gives the spectral sequence identifying the main spectral characteristics of each star class's spectrum. Each class is subdivided into ten subclasses which are denoted by numbers (0-9) after the letter (Harwit, 1973, p.515). These subclasses denote finer distinctions that do not merit separation into a whole class.

When the spectral features of stars were first investigated, the stellar spectra were found to be continuous, like those of blackbodies, with absorption and emission features (Roy, 1989, pp.138-139). The continuous spectrum of an object implies the presence of all the colors whose lines are so close together that they merge into each other

Table 2 Spectral Classification of Stars

Spectral Class	Color	Temperature(K)	Main Characteristics
W	blue	>50000	Wolf-Rayet:resembles O-class but show broad emission features caused by expanding gas shell
Q			Nova:sudden brightness increase
P			Planetary nebula:hot star with gas envelope
O	blue	>20000	lines of ionized He,N, O,and H
B	blue-white	20000-10000	neutral helium dominates
A	white	10000-7000	H lines decreasing from maximum,He absent
F	yellow-white	7000-6000	Metallic lines noticeable,weak H lines,strong calcium lines
G	yellow	6000-5000	"Solar type":weak H lines,prominent lines of metals
K	orange	4700-4000	Metallic lines dominate,faint H lines,hydrocarbon bands appear
M	red	3000-2500	strong metallic lines with wide bands produced by titanium oxide
R	orange-red	4700-4000	resembles K-class but with molecular bands of carbon compounds
N	deep red	≈2500	resembles M-class but with bands of carbon compounds
S	red	3000-2500	resembles M-class but with zirconium oxide

(Johnson, 1959, pp.59-60). In 1938, the continuous spectrum of stars was explained by Wildt. The negative ions of hydrogen in the stellar atmospheres produced the underlining continuous emission spectra found in the stars (Aller, 1963, p.191).

The brightness, or luminosity, of a star is the basis for the other parameter, called the luminosity type. The luminosity type, denoted by Roman numerals, is divided into seven categories that depend on the total output of radiant energy by a star. Table 3 lists the Roman numerals and the corresponding luminosity types. The luminosity type is related to the size of a star. Thus, a supergiant is larger than a giant which is larger than a main sequence, of which an example is the sun (Abell, 1964, p.406).

Sometimes, a letter follows the spectral classification. This denotes a variation in the spectrum of a star. Table 4 lists several common letters and the variations they represent. This variation serves as a means to further subdivide some classes of the stars.

There are also prefixes that are sometimes used. These are discussed briefly below:

c - The spectral lines are very sharp with a narrow profile.

g - denotes spectral features peculiar to giants stars.

d - denotes spectral features peculiar to dwarf stars
(Roy, 1989, p.141).

With this system of classification, the characteristics

Table 3 Luminosity Classification of Stars

Luminosity Type	Name
Ia	Bright supergiant
Ib	Normal supergiant
II	Bright giant
III	Normal giant
IV	Subgiant
V	Main sequence
VI	Subdwarf
	White dwarf

Table 4 Suffixes of Stars

Letter	Characteristics
n	broad shallow lines
s	sharp lines
e	emission line
v	variable
ev	emission lines exhibit variability
k	presence of interstellar absorption
p	peculiar spectrum usually strong metallic lines
pg	peculiarity similar to spectra of novae

of a star are anticipated by knowing the spectral class and luminosity type. Thus, a star can be compared to others of the same class and type for similarities and differences. This allows for a better understanding of stars.

Chapter 3

Theory of the Spectral Irradiance Equation

Bolometric Irradiance Equation

The magnitude of a star is the designation of the brightness of a star. The first step in this designation was the recognition that the sensation of sight varies as the logarithm of the intensity of light producing the sensation (Johnson, 1959, p.115), although today, this is believed to be wrong. Instead of being a logarithmic response, the sensation of sight is believed to be a power response (Hearnshaw, 1992). Using the principle of logarithm response, Norman R. Pogson, in the 19th century, suggested the scale of stellar magnitudes that is used today. The brighter stars have smaller magnitude numbers, and fainter stars have larger magnitude numbers. The magnitude scale is logarithmic, a difference of five magnitudes corresponding to an apparent luminosity ratio of 100. Thus, a first magnitude star is the fifth root of 100 or 2.512 times brighter than one of second magnitude which is 2.512 times brighter than a third magnitude star.

If m_1 and m_2 are the magnitudes corresponding to stars from which flux is received in the amount f_1 and f_2 , the difference of magnitude is given by

$$m_1 - m_2 = -2.512 \log\left(\frac{f_1}{f_2}\right) \quad (4).$$

This can also be written in the form:

$$\frac{f_1}{f_2} = 2.512^{-(m_1 - m_2)} \quad (5).$$

In table 5, magnitude differences are given and their corresponding approximate ratios of flux. Whether the ratio is between bright or faint stars, the given ratio corresponds to the same magnitude interval. Flux, which is an astronomical term, has been used instead of power, which is a radiometric term.

However, there are some stars whose apparent brightness is greater than that of the first-magnitude stars. For example, Sirius, the brightest-appearing star, emits approximately 10 times as much radiation as an average star of first magnitude. The sun's apparent brightness is greater than Sirius, as well as the reflected radiation from some of the planets. Table 6 shows some magnitude data (Abell, 1964, pp. 344-345).

The total apparent brightness of a star is the apparent bolometric magnitude. This is the brightness measured over all wavelengths. The bolometric magnitude is obtained only indirectly. The apparent visual magnitude, the brightness in the visual wavelengths, is measured directly. The visual magnitude along with the bolometric correction is used to find the bolometric magnitude. This correction is an estimation, that is based upon assumptions about the emissivity of a star and the temperature at the surface of a star, given in various

Table 5 Magnitude Differences and Light Ratios

Difference in magnitude	Ratio of Light
0.0	1:1
0.5	1.6:1
0.75	2:1
1.0	2.5:1
1.5	4:1
2.0	6.3:1
2.5	10:1
3.0	16:1
4.0	40:1
5.0	100:1
6.0	251:1
10.0	10,000:1
15.0	1,000,000:1
20.0	100,000,000:1
25.0	10,000,000,000:1

Table 6 Some Magnitude Data

Object	Magnitude
Sun	-26.5
Full Moon	-12.5
Venus (at brightest)	-4.0
Jupiter; Mars (at brightest)	-2.0
Sirius	-1.4
Aldebaran	1.0
Polaris (North Star)	2.02
Vega	0.03
Betelgeuse	0.50
Naked-eye limit	6.5
Binocular limit	10.0
6-inch telescope limit	13.0
200-inch (visual) limit	20.0
200-inch photographic limit	23.5

astronomy and astrophysics handbooks. The bolometric correction is defined as the difference between the bolometric and visual magnitudes of a star

$$BC = m_{bol} - m_v \quad (6).$$

Therefore, the bolometric magnitude is

$$m_{bol} = BC + m_v \quad (7)$$

(Harwit, 1973, pp.510-511). Dividing the fluxes, or powers, by the area of the incident surface, the fluxes can be changed to irradiances in equation 5. Thus, the bolometric irradiance is

$$E_1 = E_2 * 2.512^{-(m_{1bol} - m_{2bol})} \quad (8).$$

For a star, the total irradiance outside Earth's atmosphere can be obtained by substituting the irradiance for a hypothetical reference star with $m_{bol2}=0$ star into equation 8:

$$E = 2.48 \times 10^{-12} * 2.512^{-m_{bol}} \quad \text{W cm}^{-2} \quad (9)$$

where $m_{1bol} = m_{bol}$ is the apparent bolometric magnitude for the star and $E_1 = E$ (Zombeck, 1990, p.102).

Spectral Irradiance Equation

The spectral irradiance equation for a star is based on

the assumption that the bolometric irradiance of a star can be distributed as a blackbody curve with a blackbody temperature equal to an effective temperature of a star. This equation finds the spectral irradiance for a star outside the atmosphere of the Earth. The effective temperature of the star is based on the luminosity and surface area of the star. Thus, the spectral irradiance equation needs the effective temperature and bolometric corrections, which are found in various astronomy and astrophysics books.

The effective temperatures and bolometric corrections vary with the spectral class and luminosity type. The temperatures and corrections used for the supergiant and giant stars are listed in tables 7 and 8 where the hotter giant stars are the same as the supergiant stars (Johnson, 1967, pp. 196-200). Those used for O and B class main sequence stars are listed in table 9 (Code, 1975, p.237). Those for the remaining main sequence stars are in table 10. The temperatures and corrections for dwarf stars are the same as the main sequence stars (Zombeck, 1990, pp.68-70). These tables list the temperatures and correction used in calculating the theoretical values.

The spectral irradiance of a star outside the atmosphere of the Earth can be found by two different calculations. These calculations obtain the same result. One is referred to as the Zombeck method; the other is referred to as the bolometric/blackbody method.

Table 7 Bolometric Corrections and Effective Temperatures of Supergiant Stars (Ia,Ib,II)

Spectral Class	B.C.	Temperature(K)
B0	-2.29	21000
B1	-1.82	16000
B2	-1.53	14000
B3	-1.27	12800
B5	-0.91	11500
B6	-0.85	11000
B7	-0.75	10500
B8	-0.64	10000
B9	-0.52	9700
A0	-0.38	9400
A1	-0.30	9100
A2	-0.21	8900
A5	+0.01	8300
F0	+0.14	7500
F2	+0.13	7200
F5	+0.11	6800
F8	+0.08	6150
G0	+0.04	5800
G2	-0.04	5500
G5	-0.13	5100
G8	-0.15	5050
K0	-0.22	4900
K1	-0.28	4700
K2	-0.35	4500
K3	-0.50	4300
K4	-0.68	4100
K5	-1.10	3750
M0	-1.17	3660
M1	-1.26	3600
M2	-1.39	3500
M3	-1.80	3300
M4	-2.44	3100
M5	-3.23	2950

Table 8 Bolometric Corrections and Effective Temperatures of Giant Stars (III)

Spectral Class	B.C.	Temperatures (K)
G5	-0.20	5010
G8	-0.21	4870
K0	-0.30	4720
K1	-0.36	4580
K2	-0.42	4460
K3	-0.59	4210
K4	-0.79	4010
K5	-1.08	3780
M0	-1.17	3660
M1	-1.25	3600
M2	-1.41	3500
M3	-1.80	3300
M4	-2.44	3100
M5	-3.23	2950
M6	-4.15	2800

Table 9 Bolometric Corrections and Effective Temperatures of Hotter Main Sequence Stars (IV-V)

Spectral Class	B.C.	Temperatures (K)
O7	-3.30	35400
O8	-3.22	34100
O9	-3.18	33600
O9.5	-3.10	32700
B0	-3.01	31400
B0.5	-2.85	29300
B1	-2.58	26000
B1.5	-2.44	24300
B2	-2.29	22700
B2.5	-2.06	20400
B3	-1.82	18100
B4	-1.55	16200
B5	-1.31	14800
B6	-1.09	13800
B7	-0.88	12900
B8	-0.54	11300
B9	-0.36	10400
A0	-0.17	9500

Table 10 Bolometric Corrections and Effective Temperatures of Main Sequence Stars (IV-V)

Spectral Class	B.C.	Temperature (K)
A2	-0.25	9000
A5	-0.15	8620
A7	-0.12	8190
F0	-0.08	7240
F2	-0.06	6930
F5	-0.04	6540
F8	-0.05	6200
G0	-0.06	5920
G2	-0.07	5780
G5	-0.10	5610
G8	-0.15	5490
K0	-0.19	5240
K2	-0.25	4780
K5	-0.65	4410
K7	-0.90	4160
M0	-1.20	3920
M1	-1.48	3680
M2	-1.76	3500
M3	-2.03	3360
M4	-2.31	3230
M5	-2.62	3120
M8	-4.20	2660

The derivation of the first calculation, Zombeck method, is straightforward. The spectral irradiance at each wavelength needs to be calculated. The equation used in this calculation is the total bolometric irradiance equation (equation 9) where m_{bol} is found from its relation to the bolometric correction and apparent visual magnitude. A fraction of radiation given off by the source is associated with each wavelength. This gives the equation used by the Zombeck method which gives the spectral irradiance as

$$E_{\lambda} = \frac{M_{\lambda}}{M} E \quad (10).$$

After substitutions, this equation can be written

$$E_{\lambda} = \frac{1.64 \times 10^{20} * 2.512^{-m_{bol}}}{\lambda^5 T_e^4 \left(e^{\frac{1.44 \times 10^8}{\lambda T_e}} - 1 \right)} \quad \text{W cm}^{-2} \text{ \AA}^{-1} \quad (11)$$

where T_e is the effective temperature in Kelvins, λ is in angstroms and m_{bol} is calculated from equation 7. This equation, equation 11, simplifies the calculation of spectral irradiance of a star using a computer program such as Zomirrad.for in appendix A of this paper (Zombeck, 1990, p.103).

The other calculation, the bolometric/blackbody method, is derived by finding first the irradiance between two given wavelengths and then dividing by the bandwidth to obtain the

spectral irradiance. Like the Zombeck method, it finds the fraction of radiation of the source at each wavelength; however, this fraction is found for a given bandwidth with the given wavelength at its center.

First, the bolometric irradiance is calculated using equation 9. Then, the fraction is found for the given bandwidth. This can be done by integrating Planck's function for the irradiance in a given bandwidth

$$M_{\lambda_1-\lambda_2} = \int_{\lambda_1}^{\lambda_2} M_{\lambda} d\lambda \quad \text{W cm}^{-2} \quad (12)$$

and by evaluating equation 12 at lower and upper boundary points of the bandwidth and then dividing the result by the Stefan-Boltzmann Law (equation 3). This fraction is then multiplied by the bolometric irradiance. Thus, the irradiance in the given bandwidth is found. The spectral irradiance is calculated simply by dividing the irradiance by the bandwidth. The spectral irradiance using the bolometric/blackbody can be written

$$E_{\lambda} = \frac{M_{\lambda_1-\lambda_2}}{M} \frac{E}{bw} \quad (13)$$

where bw is the bandwidth in angstroms.

Sample Calculation Using the Bolometric/Blackbody Method

Star: Mu Ser (A0V)	$m_v = 3.53$
center wavelength = 5000 Å	$T_{\odot} = 9500 \text{ K}$

bandwidth = 50 Å

$$BC = -0.17$$

$$\lambda_1 = 4975 \text{ Å}$$

$$\lambda_2 = 5025 \text{ Å}$$

The apparent bolometric magnitude is

$$m_b = BC + m_v = -0.17 + 3.53 = 3.36 \quad (S-1).$$

With the bolometric magnitude the bolometric irradiance is found to be

$$E = 2.48E-12 * 2.512^{-m_{bol}} = 1.123E-13 \text{ W cm}^{-2} \quad (S-2).$$

The exitance in the bandwidth centered on the wavelength 5000 Å is calculated to be

$$M_{\lambda_1-\lambda_2} = \int_{\lambda_1}^{\lambda_2} \frac{3.74 \times 10^{30}}{\lambda^5 \left(e^{\frac{1.44 \times 10^8}{\lambda * 9500}} - 1 \right)} d\lambda = 0.0303 \quad (S-3)$$

and the total exitance is

$$M = \sigma * (9500^4) = (5.67 \times 10^{-12}) (9500^4) = 4.62 \text{ W cm}^{-2} \quad (S-4)$$

Thus, the spectral irradiance for Mu Ser at wavelength 5000 Å is

$$E_\lambda = \frac{M_{\lambda_1-\lambda_2}}{M} \frac{E}{bw} = 1.476E-17 \text{ W cm}^{-2} \text{ Å}^{-1} \quad (S-5)$$

The average experimental spectral irradiance at this wavelength from the Willstrop data is $1.78 \times 10^{-17} \text{ W/ cm}^2 / \text{Å}$

with a deviation of $\pm 0.03 \times 10^{-17}$.

This calculation can be done easily and well by using the computer program, Irrad2.for in appendix A, which accomplishes the integration by an iterative process (McCoy, 1991-1992).

Chapter 4

Assessment of the Spectral Irradiance Equation

The assessment of the spectral irradiance equation (equation 11) was accomplished using of astronomical data sets found in various journals and reports. The calculation of the theoretical values required the use of the two computer programs in the appendix.

The first data set was published by R. V. Willstrop. The data covered most of the visual band. It ranged from 4000 to 6500 Å in steps of 100 Å with four measurements at each wavelength except the last wavelength 6500 Å, which had one measurement. These data were taken with a spectrometer that had a bandwidth of 50 Å for each wavelength. The data were corrected to give the spectral irradiance received outside the Earth's atmosphere. The data were also normalized to a star of the same spectral type but of apparent magnitude $V = 0.00$ using equation 5 with units of ergs per centimeter squared per second per angstrom. These data were corrected for the atmosphere by atmospheric absorption coefficients tabled by Willstrop (Willstrop, 1965, p.98).

The Willstrop data were changed to give the spectral irradiance for a given star outside the atmosphere for the given magnitude of the star. To accomplish this, the average experimental irradiance for a star at each wavelength was calculated. The units were converted to watts per centimeter squared per angstrom. Then, the average irradiance was found

by using equation 5:

$$E_1 = E_2 * 2.512^{(-m_1 + m_2)} \quad (14)$$

where E_2 was the Willstrop data, $m_2=0$ and m_1 was the apparent visual magnitude of the star.

After the data for a number of stars were changed, the theoretical spectral irradiance was calculated using the spectral irradiance equation. The experimental and theoretical spectral irradiances were then plotted and compared. Figures 3-5 are examples of the plotted graphs. Figures B-1 through B-11 in appendix B contain further examples of the graphs. These figures show the Willstrop data as the squares and the calculations using equation 13 as the curve. The first heading of the graphs indicate the identification of the star and the spectral class and luminosity type in parenthesis. The second heading indicates the effective temperature used to calculate the theoretical curve. The calculations were done by using the Irrad2.for program. The figures are plots of spectral irradiance versus wavelength.

The other main data set was one of the information sets in the Selected Astronomical Catalogs on CD-ROM from Astronomical Data Center (ADC). The data set used was compiled by James E. Gunn and L.L. Styrer. These data covered the range 3130 to 10800 Å which is basically the ultraviolet, visible and near infrared spectral regions and were given as ratios of

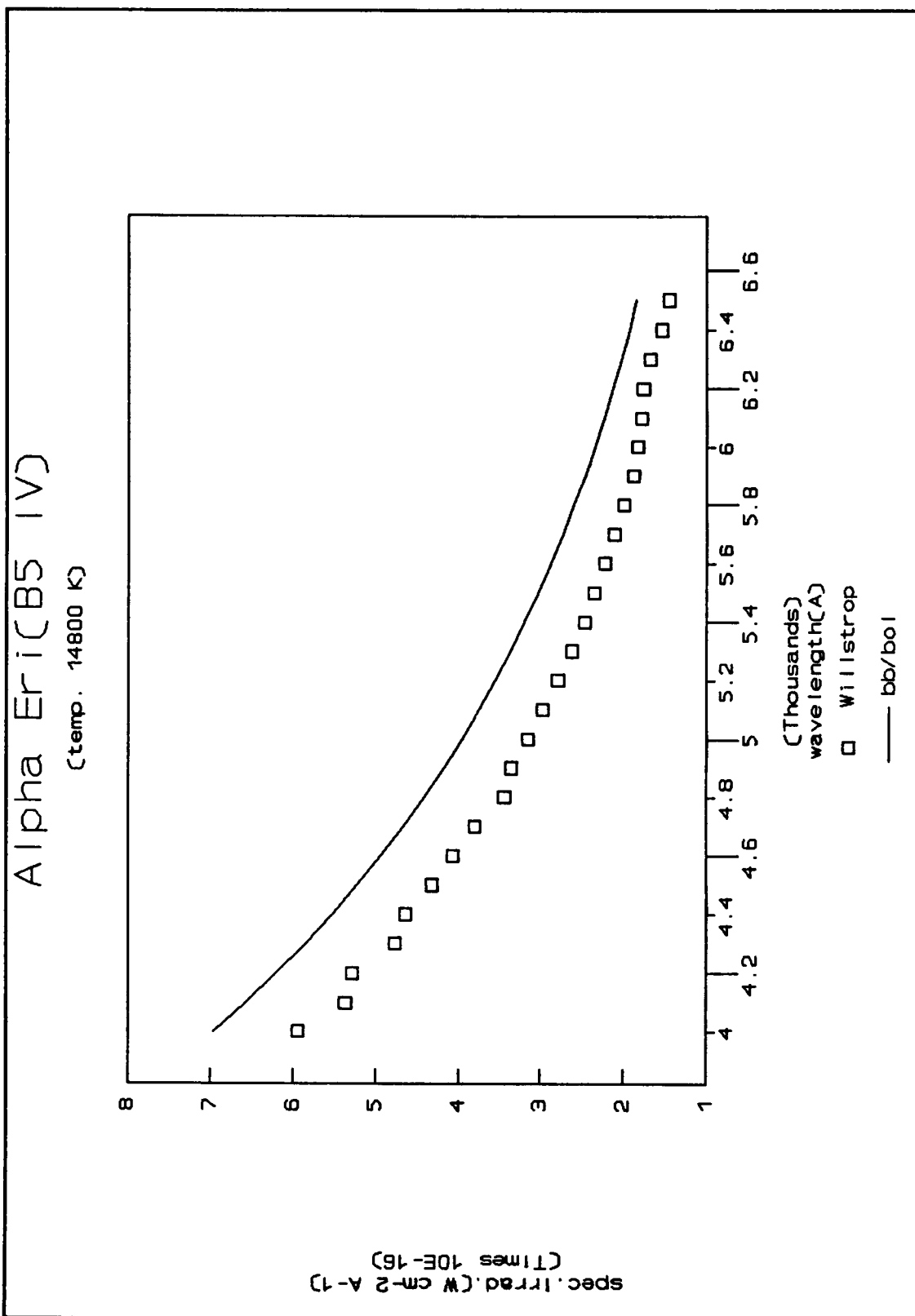


Figure 3 Spectral Irradiance of Alpha Eri

Kappa Cet (G5 V)

(temp. 5610 K)

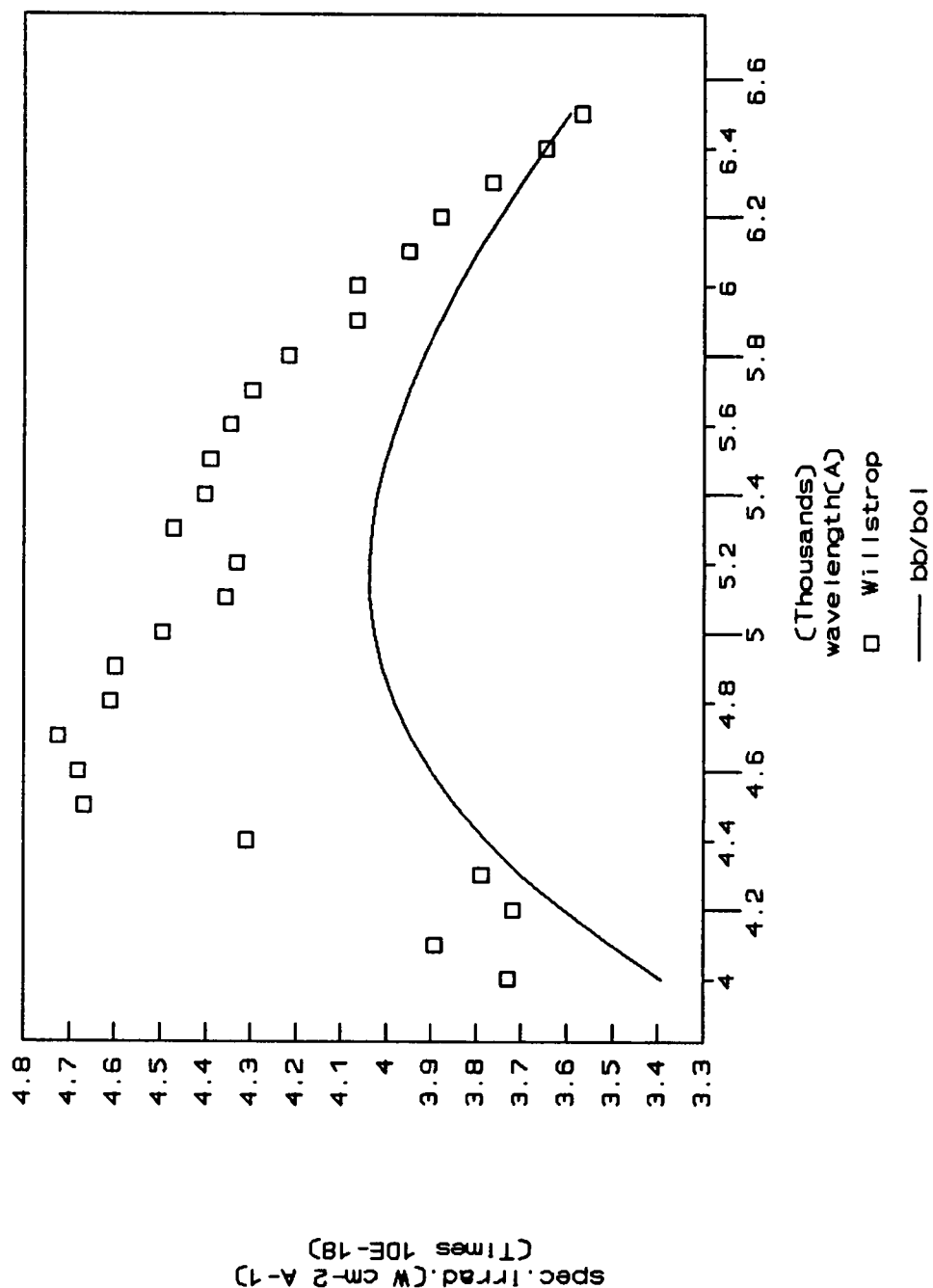


Figure 4 Spectral Irradiance of Kappa Cet

HD 217987 (M2V)

(temp. 3500 K)

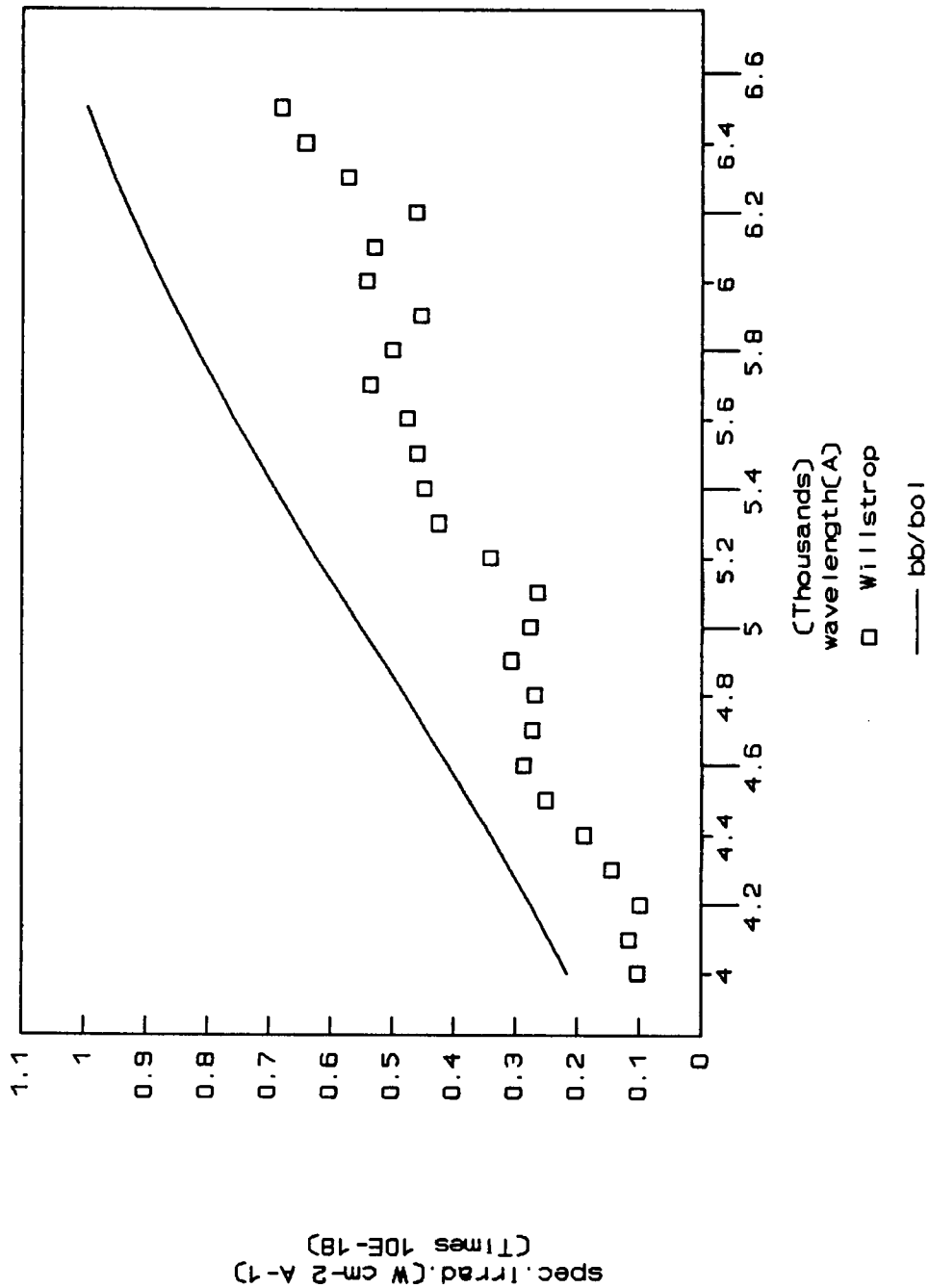


Figure 5 Spectral Irradiance of HD 217987

the spectral irradiance measured to the calculated spectral irradiance at the wavelength 5500 Å. These data were taken on the surface of the Earth and then corrected to above atmosphere by use of standard extinction curves (Gunn, 1983).

The data were changed to the form needed by multiplying the data point by the calculated spectral irradiance of the star at 5500 Å.

$$E(\nu) = \text{datapoint} * E(m_v=0, \lambda=5500\text{\AA}) \quad (15)$$

This gave the data units of ergs per centimeter squared per second per hertz. These were then converted to watts per centimeter squared per angstrom by

$$E(\lambda) = E(\nu) * \frac{c}{\lambda^2} \times 10^{-7} \text{ W cm}^{-2} \text{ \AA}^{-1} \quad (16)$$

(Styker, 1992).

After the experimental data were in the form needed, they were compared to the theoretical calculations. This comparison simply involved comparing visually the spectral graphs of the empirical data to the calculated data. Figures 6-8 are examples of the plotted graphs. Figures B-12 through B-18 in appendix B contain further examples of the graphs. These figures show the Styker data and calculations, which were done by using the Zomirrad.for program. The calculations, using equation 11, are the smooth curve on the graphs while the Styker data are the irregular curve on the graph. The headings

9 Vul (B7V)

(temp. 12900 K)

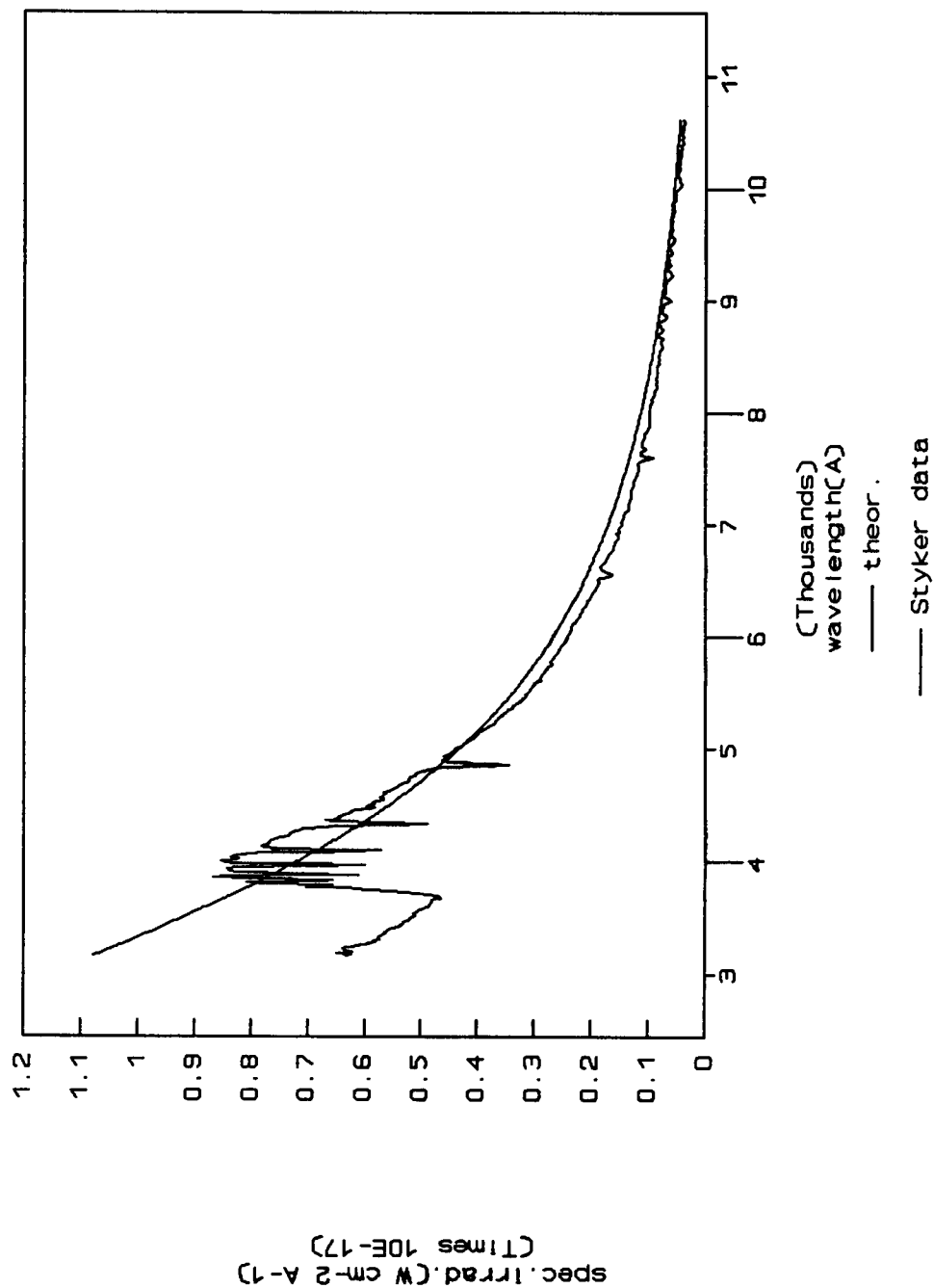


Figure 6 Spectral Irradiance of 9 Vul

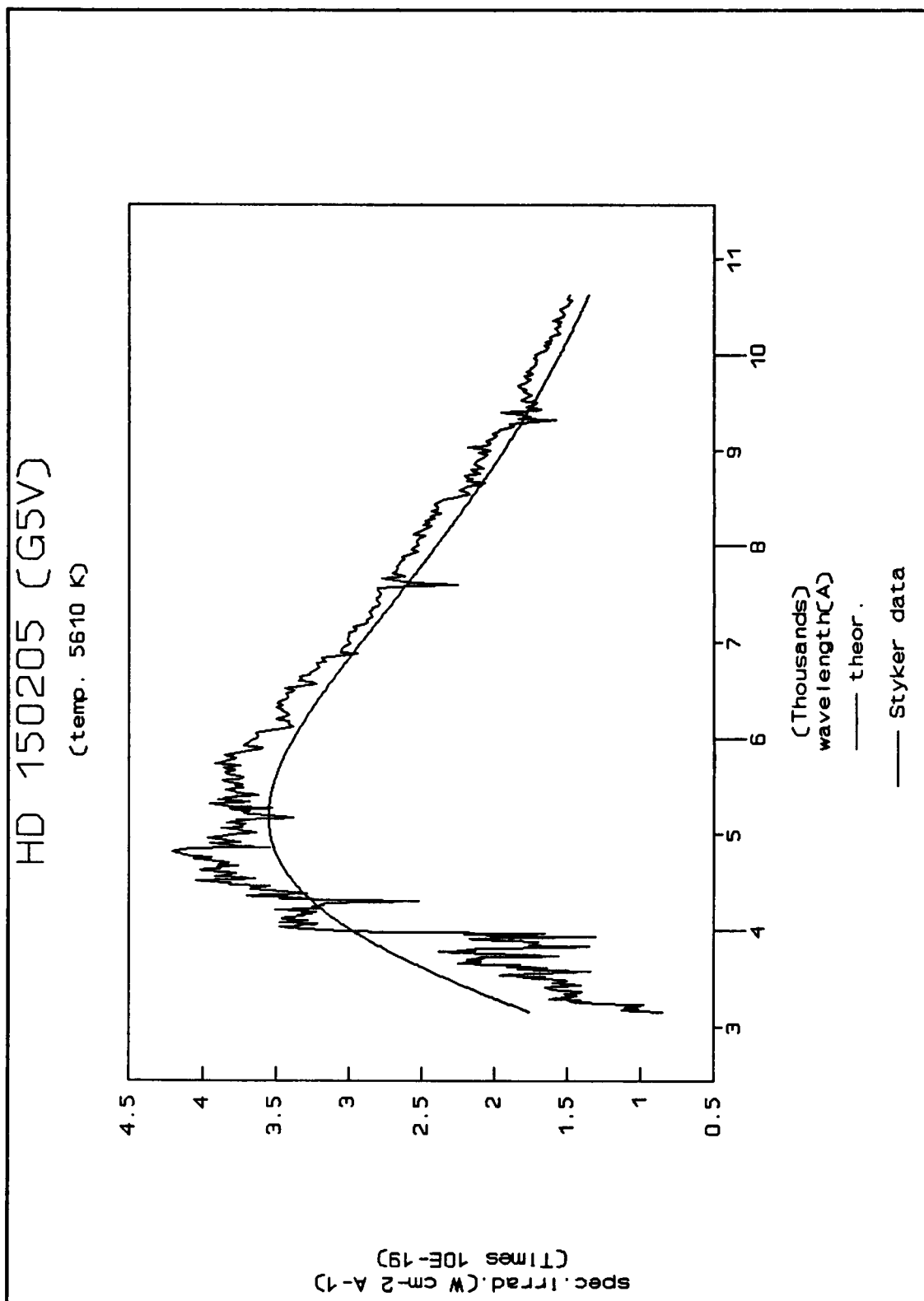


Figure 7 Spectral Irradiance of HD 150205

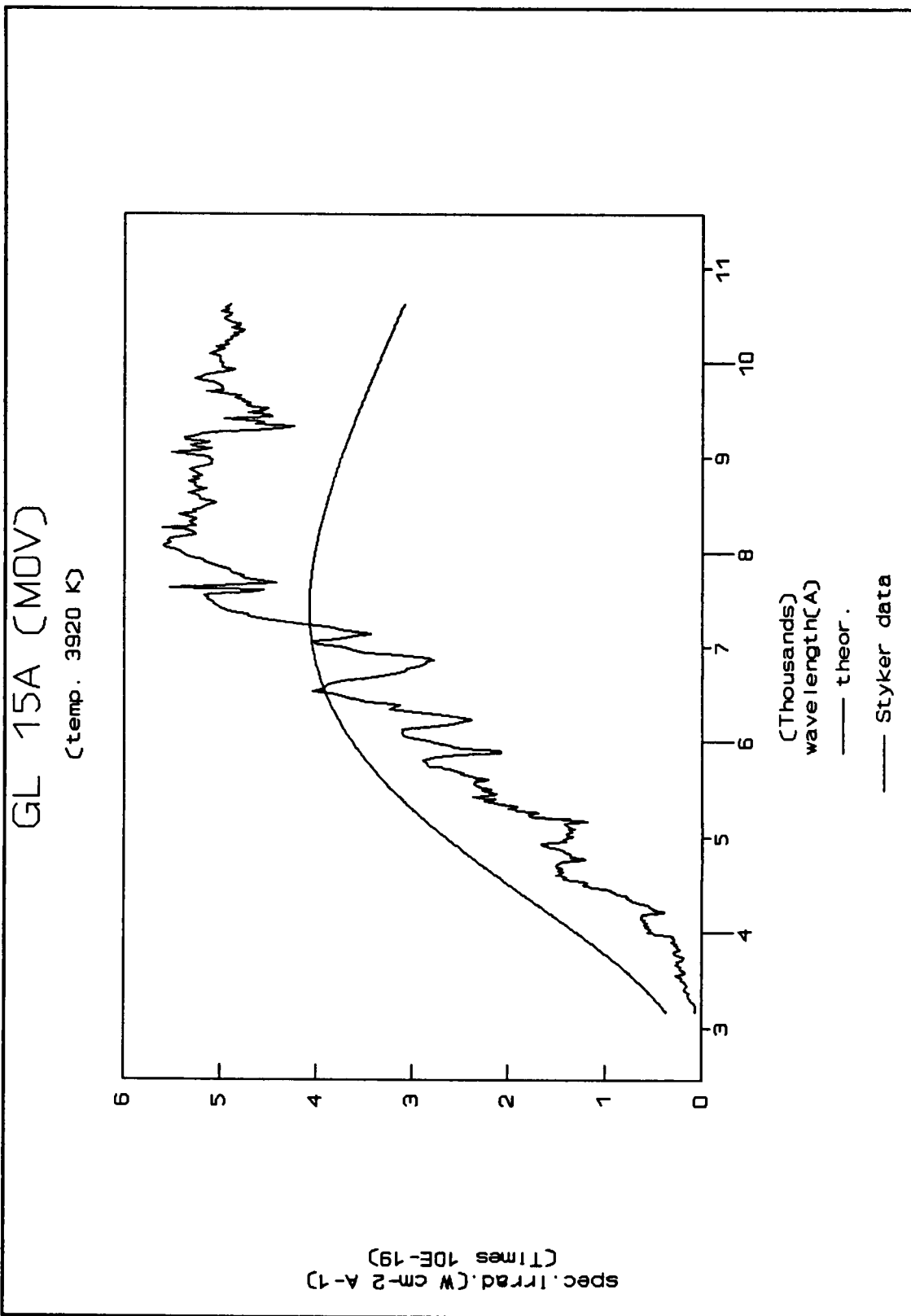


Figure 8 Spectral Irradiance of GL 15A

on these graph are the same as those for the Willstrop data. The figures are plots of spectral irradiance verses wavelength.

Two ultraviolet data sets were examined to determine if the equation (equation 11) was valid in the ultraviolet region. These were UVBS data from ADC CD-ROM (Nagy, 1981) and OAO-2 (Code and Meade, 1979). Both sets were in the units needed. These data were compared to the theoretical data. This comparison revealed problems which are discussed in Chapter 5 of this thesis. It was concluded that with the given temperature, the equation did not work; however, if the effective temperature used for the visual and infrared region was lowered, the equation would be of use in the ultraviolet region as well.

The accuracy of the spectral irradiance equation compared to the Willstrop data in the wavelength used varied with class and type. Table 11 lists the spectral class and luminosity type with the percent error. This table shows the accuracy of the equation. The percent error was found by using:

$$\%e = \left| \frac{\text{experimental} - \text{theoretical}}{\text{experimental}} \right| \times 100 \quad \% \quad (17)$$

The equation had the best accuracy in the main sequence F-G stars; however three of the classes had very large percent errors. Thus, the equation is a good first order approximation for F-G main sequence and is a good rough approximation for

Table 11 Percent Error of the Theoretical Values as Compared to the Willstrop data

Class and Type	Percent Error
Supergiant	
A-K	30%
B5-B9	40%
Giants	
B5-B9,M	40%
K	45%
A-G	30%
Main Sequence	
B-A,K	30%
F-G	25%
Supergiant	
B0-B4,M	large errors
Main Sequence	
M	large errors

most of the other classes in the visual region. Table 11 does not include the O class and B0-B4 giants due to insufficient experimental data.

For the Styker data, the accuracy of the equation varied greatly as class and type changed. Table 12 lists the percent errors in each of the three spectral regions covered by the Styker data with the class and type of star. This table shows the accuracy of the equation. The percent errors were calculated using equation 17. The spectral irradiance equation had the best accuracies in the visual and infrared regions for the main sequence F-G stars and in all three regions for the main sequence K stars; however, the equation was not accurate in the ultraviolet region. The equation is a good first order approximation for some of the classes and is a good rough approximation for other classes; however, it is not a good approximation in the ultraviolet region. Table 12 does not list the M main sequence stars because the percent errors were large in most of the wavelength regions. It does not include supergiant stars, O main sequence stars, O-B giant and F-G4 giant stars due to insufficient experimental data.

Table 12 Percent Error of the Theoretical Values as Compared to the Styker Data

Class and Type	% error UV	% error VIS	% error IR
Giants			
A	large	40%	40%
G5-K	large	20%	20%
M	large	large	20%
Main Sequence			
B-A	large	40%	40%
F-G	large	25%	20%
K	20%	21%	20%

Chapter 5

Conclusion

Sources of Error

Most of the errors stem from the assumption that stars are blackbodies which they are not. The inaccuracies due to this assumption is most evident in the ultraviolet spectrum of very hot stars (Harwit, 1973, p. 384). There are several other sources of error. Some of these are concerned with the ultraviolet region while the others are associated with estimations that are being updated as technology allows.

The bolometric correction is actually an estimation based on some qualitative assumptions which are not simple. Thus, errors are introduced into the theoretical calculations. However, in the recent decade, new data on the stellar brightness values in the ultraviolet and infrared regions have been taken. These new data are being incorporated by astronomers to obtain more reliable bolometric corrections (Harwit, 1973, p. 511).

A major source of error arises from the concept of the effective temperature and its application to the problem. The effective temperature is the temperature that a black sphere of the same radius would have if its total energy output is the same as the star. This requires that the total energy output and radius of the star is known; however, the measurement of the radius is very difficult and not accurate. The temperature is not directly observable except perhaps for

the sun. Several ways of obtaining the temperature indirectly have been used; unfortunately, the temperatures are only as reliable as these indirect methods. Thus, the errors in the predicted temperatures carry into the theoretical calculations (Aller, 1963, pp. 268-269).

The Balmer discontinuity presents a source of error. The Balmer discontinuity results from a sharp rise in ultraviolet absorption at wavelengths corresponding to the Balmer series produced by excited atoms in the outer atmosphere of a star. The excited atoms producing the absorption are hydrogen atoms in their first excited states. This absorption in the ultraviolet and short wavelength regions is caused by a bound-free transition from the $n=2$ level of the hydrogen atom. (Harwit, 1973, p.518). The magnitude of the Balmer discontinuity is defined by

$$D = \log \left(\frac{I(>3650\text{\AA})}{I(<3650\text{\AA})} \right) \quad (18)$$

where $I(>3650 \text{ \AA})$ is the intensity from a Planckian curve on the long wavelength side of the Balmer discontinuity and where $I(<3650 \text{ \AA})$ is the intensity derived from the energy distribution short wavelength of the Balmer discontinuity. Table 13 shows a few values of the discontinuity for a given spectral class. These values change for each class (Aller, 1963, pp.278-279).

In the ultraviolet region, several other problems occur.

Table 13 Balmer Discontinuities of Main Sequence Stars

Spectral Class	D
O7	0.04
O9	0.06
B0	0.08
B1	0.10
B2	0.14
B3	0.21
B5	0.27
B8	0.38
B9	0.47
A0	0.51
A2	0.52
A3	0.49
A5	0.46
A7	0.41
F0	0.33
F2	0.25
F5	0.18
F8	0.13

These problems are

1. The blanketing effect is caused by absorption in the outer atmosphere of a star changing the spectrum of the escaping radiation. This effect causes the blackbody assumption not to be accurate for very hot stars such as the O and B classes which generate most of their radiation in the ultraviolet regions.

2. Strong absorption by interstellar hydrogen which is ionized by the emitted photons prevents observations lower than 912 Å except for a few nearby stars (Harwit, 1973, p.384).

3. The absorption of a star is not independent of wavelength. Its dependence is proportional to inverse λ . In the spectral regions where the absorption is high, the radiation comes from the uppermost layers while in other spectral regions the radiation comes from the deeper hotter layers. Therefore, a change in temperature for the cooler stars classes A-M occurs in the observed data (Aller, 1963, p.199).

4. The scattering and absorption of starlight are both included in the definition of interstellar extinction. Interstellar extinction is primarily confined to the plane of the galaxy which is the location of most of the interstellar gas. It is generally accepted that extinction is caused by small solid particles called grains that tend to be in the form of discrete clouds. Extinction at visual wavelengths is

dependent on approximately the inverse wavelength (Rose, 1973, p.23). Thus, insufficient knowledge regarding interstellar extinction is expected to be a source of error.

Summary

The spectral irradiance equation has been shown to be a good first order approximation to the spectral irradiance of a star in the visual and infrared spectral regions but not in the ultraviolet region; however, the technique can be improved. Several improvements involve the application of state-of-the-art data recording technologies resulting in improved estimations of the effective temperatures and bolometric corrections of stars. These improvements also can increase the knowledge and empirical data of stars in the shorter wavelength regions of the spectrum.

The spectral irradiance equation can also be improved by reducing and accounting more accurately for the sources of error. One important improvement is the altering of the equation to account for the inverse wavelength dependence of the absorption as it affects the observed radiation of the star. Taking into account the difference in temperature between the ultraviolet region and visual regions, the equation can be altered to give a better fit to the spectral irradiance of a star. These two listed improvements are examples of reducing the errors in the approximation.

In summary, the spectral irradiance equation is useful in

determining a theoretical curve that approximates the spectral irradiance of a star in the visual and infrared regions. The assessment of the equation showed that the main sequence F-G stars are the best candidates to use as calibration sources for the visual and infrared regions. In the ultraviolet region, the assumption that stars are blackbodies proved to be incorrect. The equation is only an estimation of the spectral irradiance of a star, and the use of actual data in calibrating the instruments would be much better.

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APPENDIXES

APPENDIX A

ZOMIRRAD.FOR

```

c This program calculates the spectral irradiance for a star.
c      Programmed by Valinda Kirkland
c wave.dat for input of wavelengths
c Inputs: te-effective temperature in K
c      lambac- wavelength in Angstroms
c      bc-bolometric correction
c      v- apparent visual magnitude
c      double precision bc,v,mb,ft,f
c      double precision lambac(160),te
c      integer arnu,j
c      character*24 asw

c      open(unit=25,file='starin.dat', status='unknown', form=
'formatted')
c      open(unit=30,file='grap.dat', status='unknown', form=
'formatted')
c      open(unit=35, file='wave.dat', status='old', form=
'formatted')
c      print*,'Enter star name/identification'
c      read*,'(a24)') asw
c      print*,'Enter effective temperature'
c      read*,te
c      print*,'Enter bolometric correction'
c      read*,bc
c      print*,'Enter apparent visual magnitude'
c      read*,v
c      write(25,*) asw
c      write(25,*)
c      write(25,105) int(te),bc,v
105  format('Te= ',i7,' B.C.= ',g10.2,' V= ',g10.4)
c      print*,'How many wavebands?'
c      read*,arnu
c      do 8 j=1,arnu
c          read(35,*) lambac(j)
8      continue
c      mb = bc+v
c      ft = (2.48d-12)*(2.512d0**(-mb))
110  format(a20,1p,e16.8e2,a9)
c      write(25,110) 'total irradiance is ', ft,' W cm-2'
c      write(25,*)
c      write(25,*) ' wavelength          spec. irradiance '
c      write(25,*) ' (A)                  (W cm-2 A-1)'
c      write(25,*)
c      do 9 j=1,arnu
c          f = (1.640d20)*(2.512d0**(-mb))/((lambac(j)**5)
2          *(te**4)*(exp(1.44d8/(lambac(j)*te))-1.0d0))
115  format(4p,g10.2,' ',1p,e16.8e2)
c      write(25,115) lambac(j),f

```

```
    write(30,115) lambac(j),f
9  continue
    close(unit=35,status='keep')
    close(unit=25,status='keep')
    close(unit=30,status='keep')
end
```

IRRAD2.FOR

```

c This program calculates the irradiance and spectral
c irradiance in given bandwidth for a star.
c      Programmed by Valinda Kirkland
c wave.dat input of wavelengths
c Inputs: te-effective temperature in K
c      lambdac- wavelength bandwidth is centered on in
angstrom
c      bc-bolometric correction
c      v- apparent visual magnitude
c      b- bandwidth in angstrom
      double precision bc,v,lamba1,lamba2,mb,ft,i,s,f
      double precision lambdac(30),b(30),te,n
      integer arnu,j
      character*24 asw
c
      open(unit=25, file='starin.dat', status='unknown',
form= 'formatted')
      open(unit=30, file='grap.dat', status='unknown',
form= 'formatted')
      open(unit=35, file='wave.dat', status='old',
form= 'formatted')
      print*, 'Enter star name/identification'
      read(*, '(a24)') asw
      print*, 'Enter effective temperature'
      read*, te
      print*, 'Enter bolometric correction'
      read*, bc
      print*, 'Enter apparent visual magnitude'
      read*, v
      write(25,*) asw
      write(25,*)
      write(25,105) int(te),bc,v
105  format('Te= ',i7,' B.C.= ',g10.2' V= ',g10.4)
      print*, 'How many wavebands?'
      read*, arnu
      do 8 j=1, arnu
          read(35,*) lambdac(j),b(j)
      8  continue
c s is the Stefan-Boltzmann constant
      s = 5.67d-12
      mb = bc+v
      ft = (2.48d-12)*(2.512d0**(-mb))
      write(25, '(a19,1p,e16.8e2,a7)') 'total irradiance is',
ft, ' W cm-2'
      write(25,*)
      write(25,*) 'wavelength      irradiance      spec. irrads'
      write(25,*) '      (A)              (W cm-2)      (W cm-2 A-1)'
      write(25,*)
      do 9 j=1, arnu

```

```

        lamba1 = (lambac(j) - b(j)/2)*(1E-8)
        lamba2 = (lambac(j) + b(j)/2)*(1E-8)
        n = 100.00d0
        i = simpsn(lamba1,lamba2,n,te)
        f = i*ft/(s*(te**4))
100    format(4p,g10.2,'      ',1p,e16.8e2,'      ',e16.8e2)
200    format(4p,g10.2,1p,e16.8e2,e16.8e2)
        write(25,100) lambac(j), f,f/b(j)
        write(30,200) lambac(j), f, f/b(j)
    9    continue
        close(unit=35,status='keep')
        close(unit=25,status='keep')
        close(unit=30,status='keep')
    end

c
    function simpsn(a,b,n,te)
c    computes the area under a standard normal curve
c    between a and b using Simpson's rule with n intervals
c    input arguments
c        a,b- the end point of the integrated region
c        n-the number of intervals, te-effective temperature
    double precision a,b,te,n
    double precision h,deltaz,sumodd,sumeve,z
    integer i
c    compute required increments
        h = (b-a)/n
        deltaz = 2.0d0 * h
c    compute sumodd
        sumodd = 0.0d0
        z = a + h
        do 10 i=2,n,2
            sumodd = sumodd + f(z,te)
            z = z + deltaz
        10 continue
c    compute sumeve
        sumeve = 0.0d0
        z = a + deltaz
        do 20 i=2,n-2,2
            sumeve = sumeve + f(z,te)
            z = z + deltaz
        20 continue
c    compute integral
        simpsn=(f(a,te) + f(b,te)+4.0d0*sumodd + 2.0d0*sumeve)
        2      *(h/3.0d0)
        return
    end

c
    function f(x,te)
c    computes function
    double precision h1,c,k,x,pi,te
    parameter(pi=3.14159d0)
    h1 = 6.63d-34

```

```

c = 3d+10
k = 1.3807d-23
f= (2.0d0*pi*h1)*(c**2)/((x**5) *(exp(h1*c/(x*k*te))
2      -1.0d0))
return
end

```

APPENDIX B

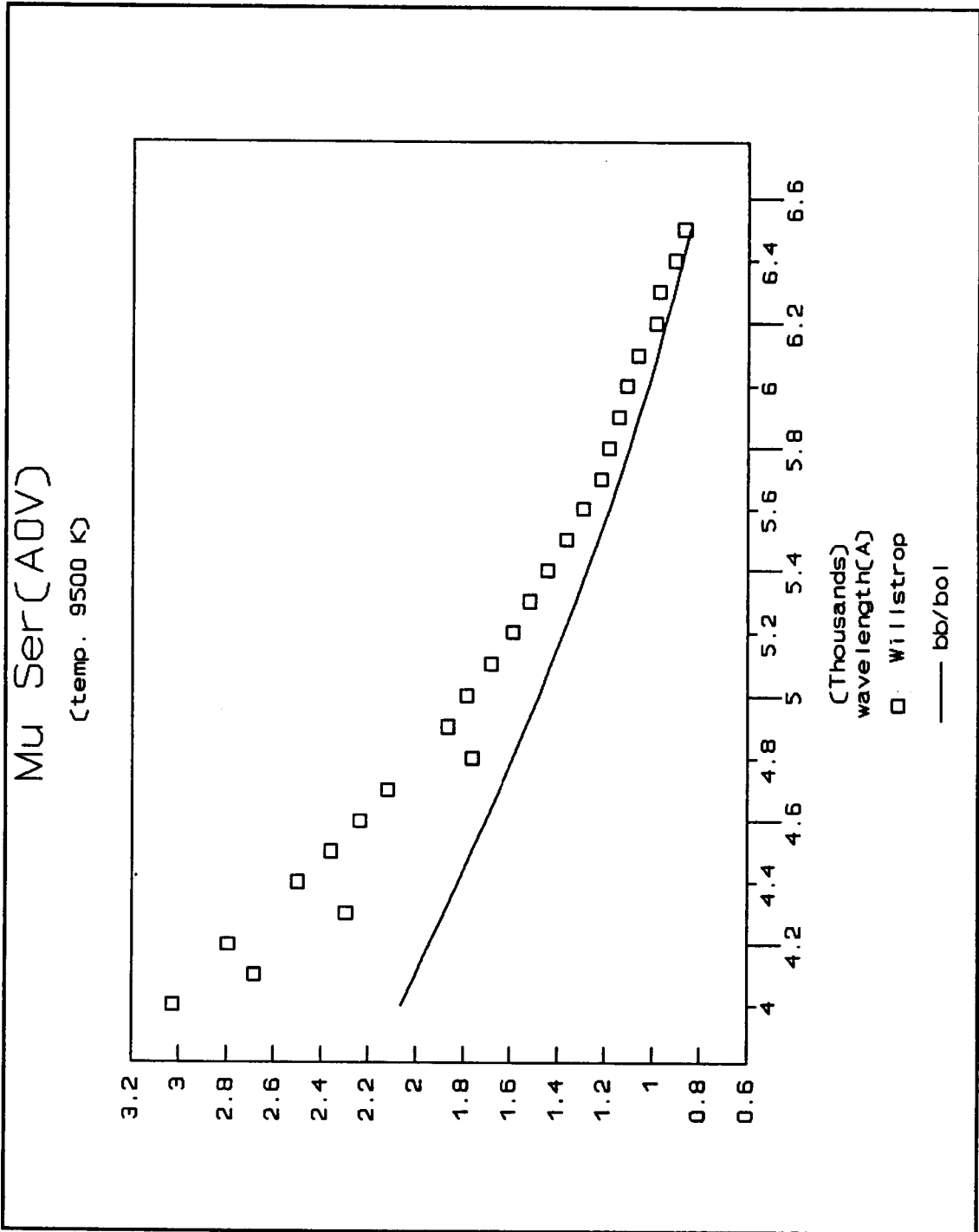


Figure B-1 Spectral Irradiance of Mu Ser

Psi Cap(F5V)

(temp. 6540 K)

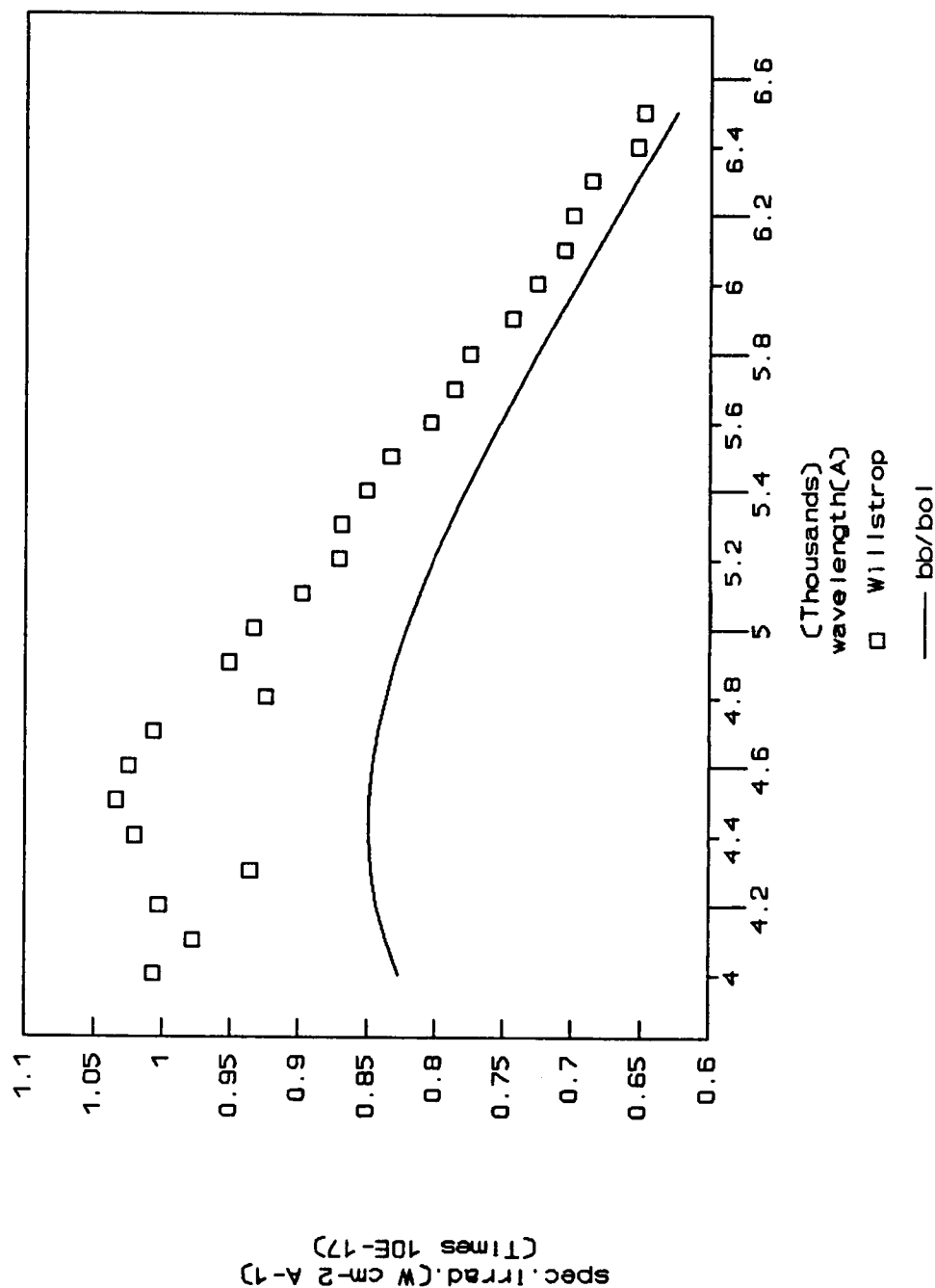


Figure B-2 Spectral Irradiance of Psi Cap

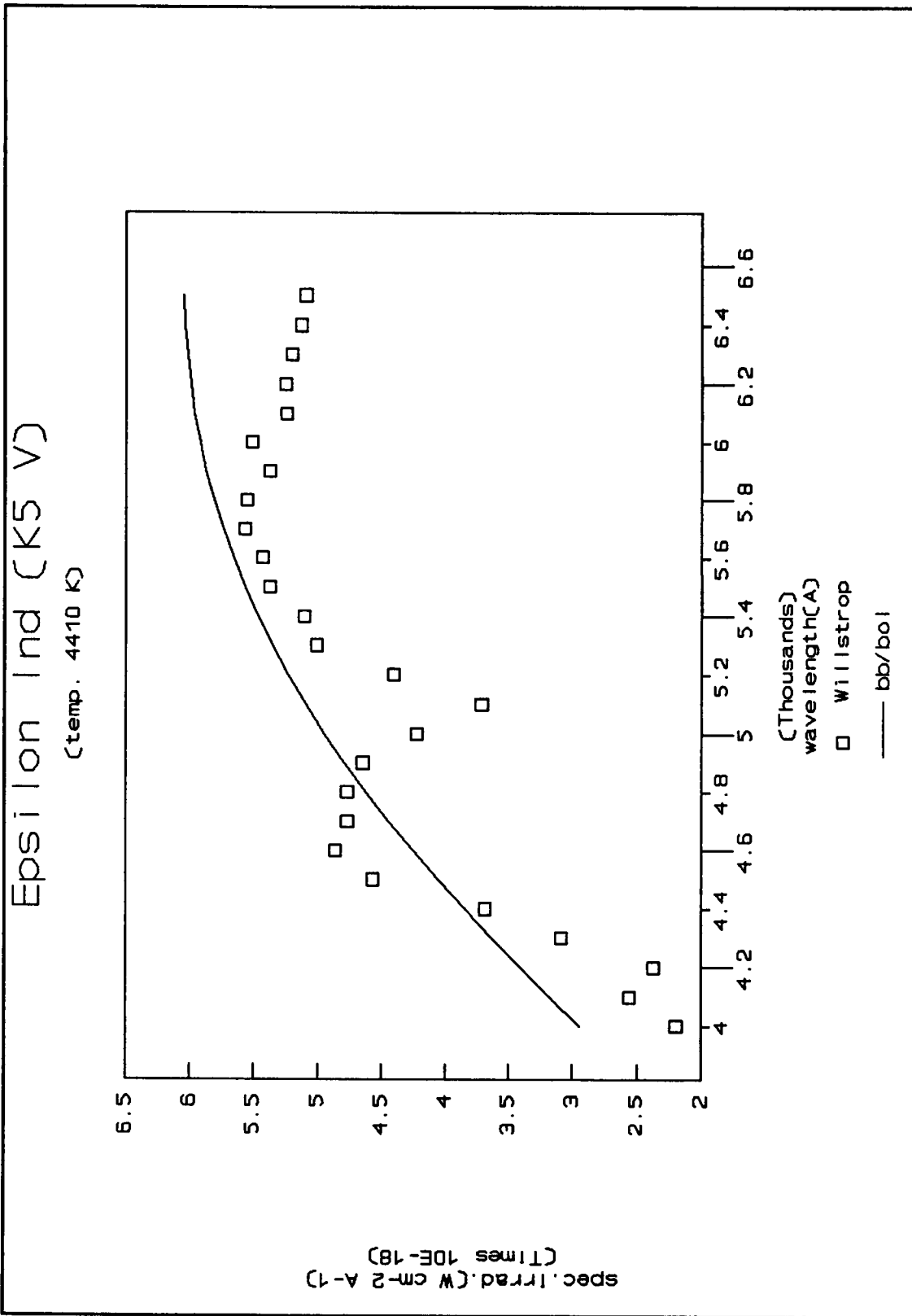


Figure B-3 Spectral Irradince of Epsilon Ind

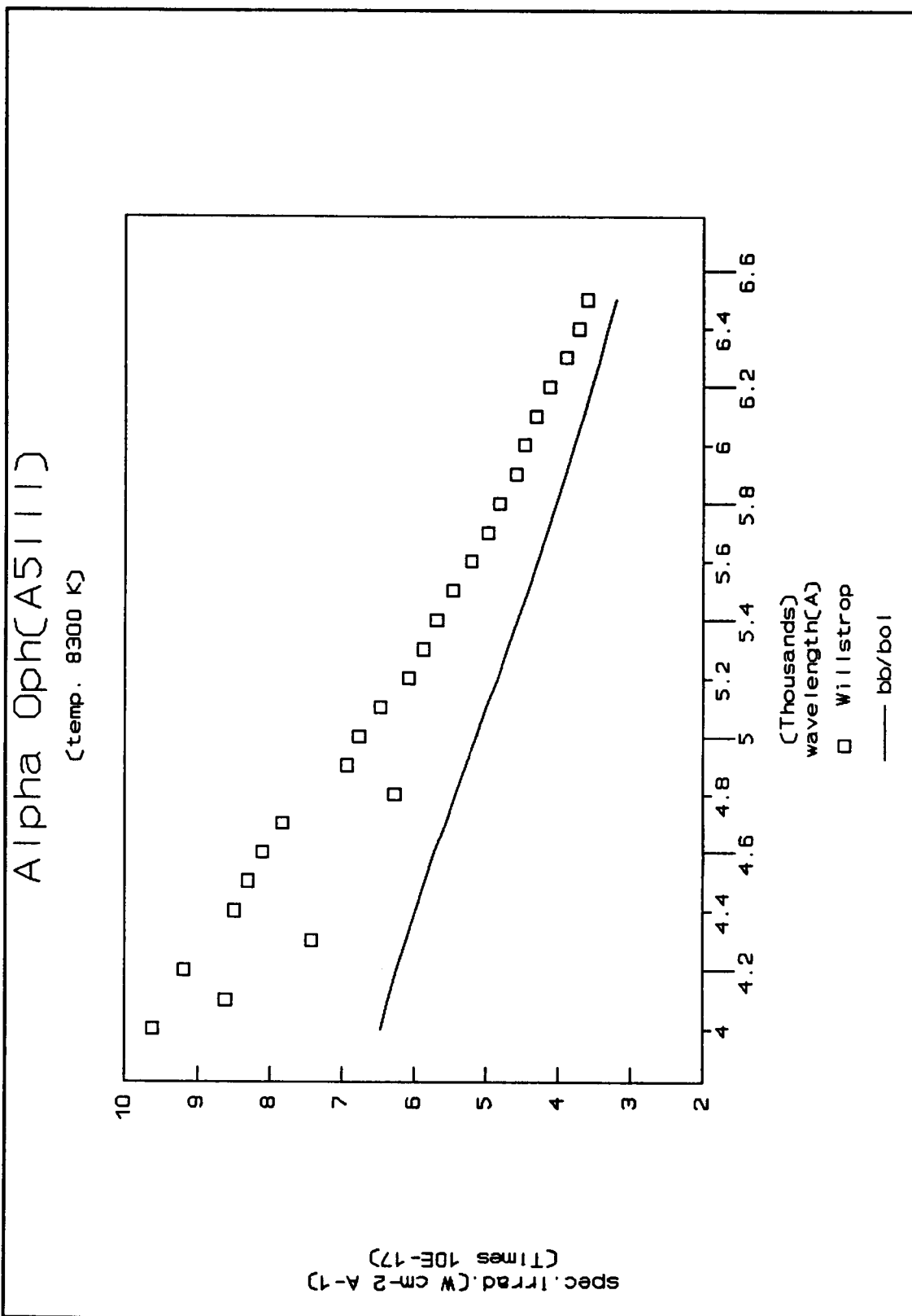


Figure B-4 Spectral Irradiance of Alpha Oph (Willstrop)

Beta Lep(G5111)

(temp. 5010 K)

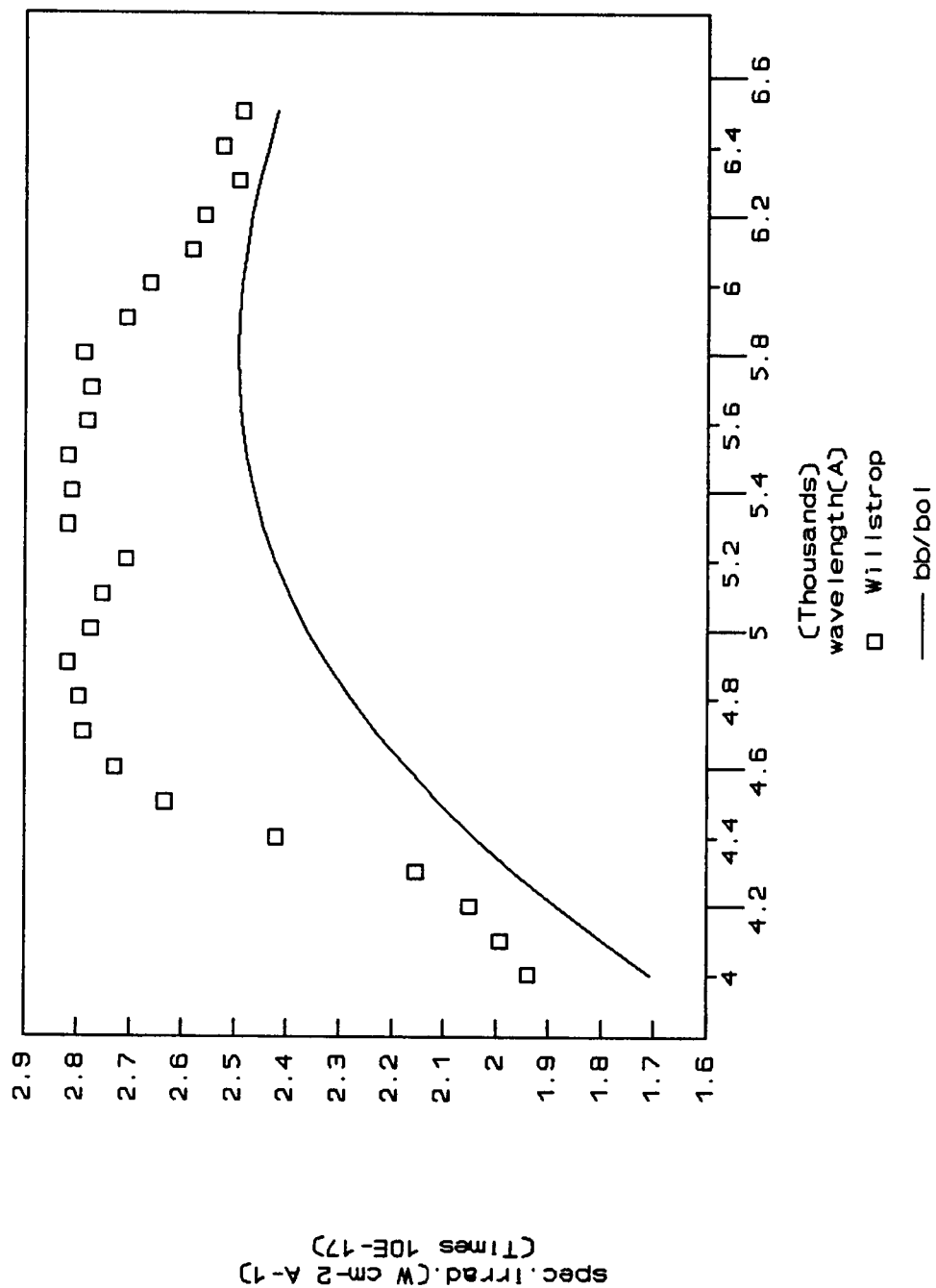


Figure B-5 Spectral Irradiance of Beta Lep

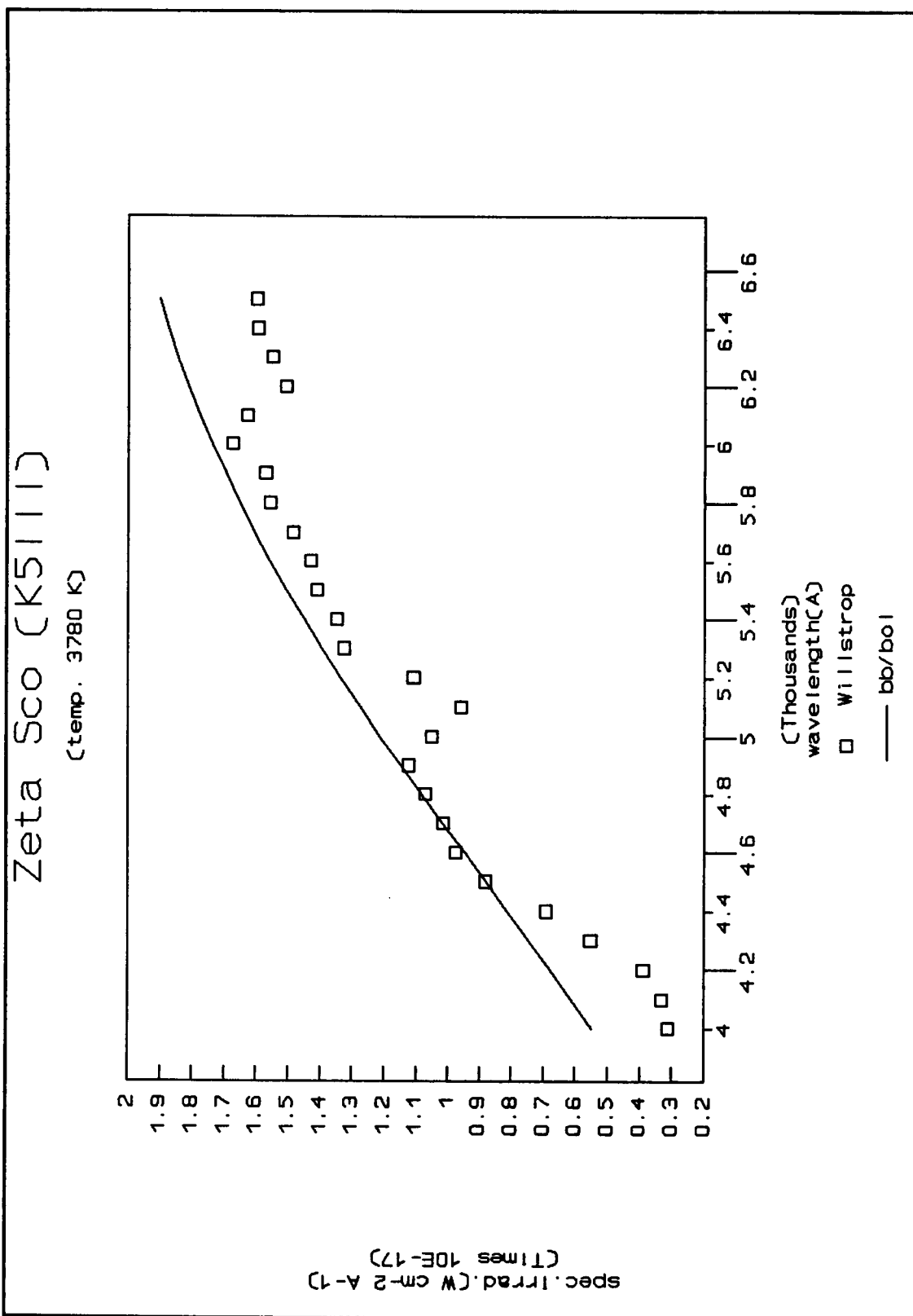


Figure B-6 Spectral Irradiance of Zeta Sco

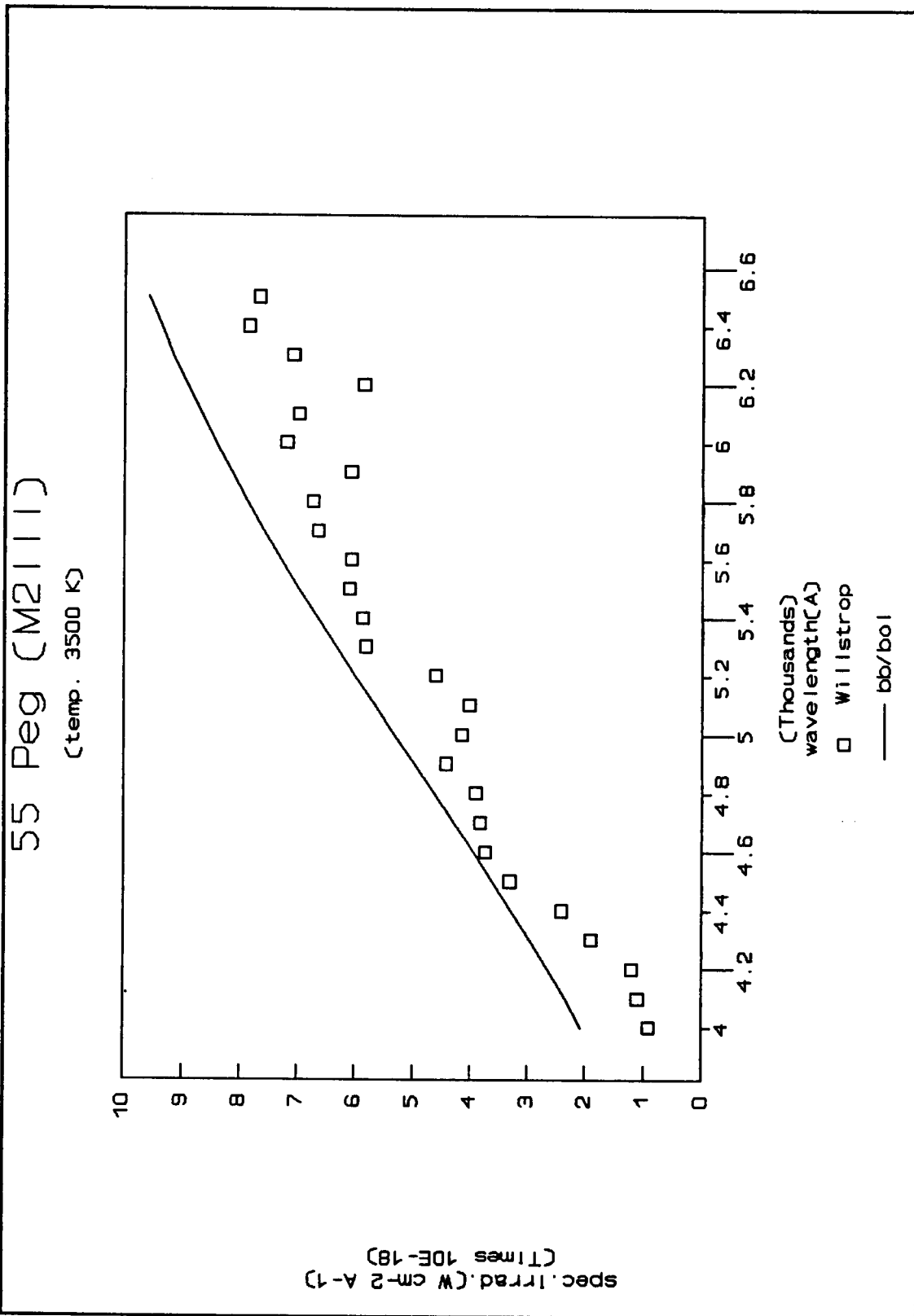


Figure B-7 Spectral Irradiance of 55 Peg

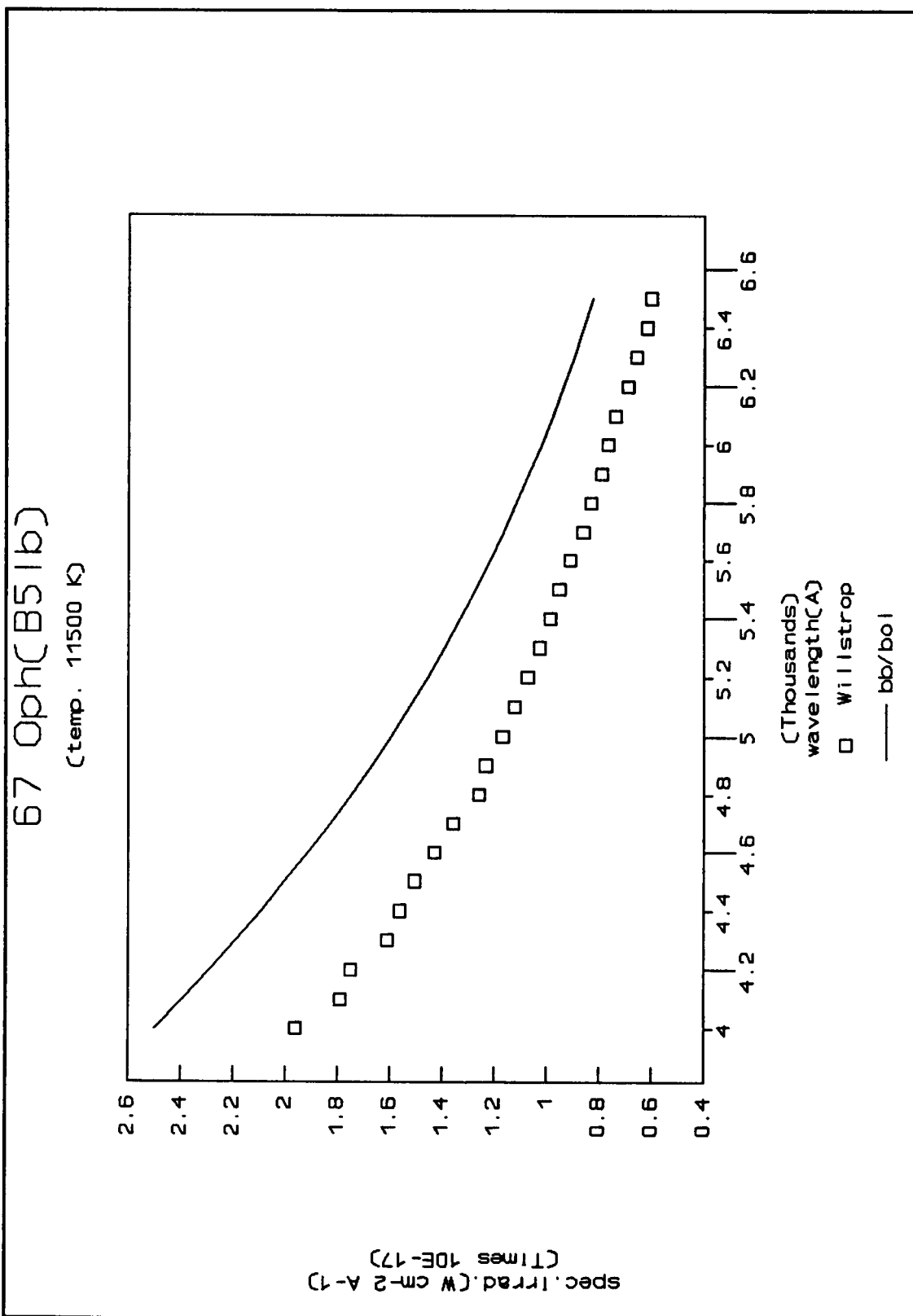


Figure B-8 Spectral Irradiance of 67 Oph

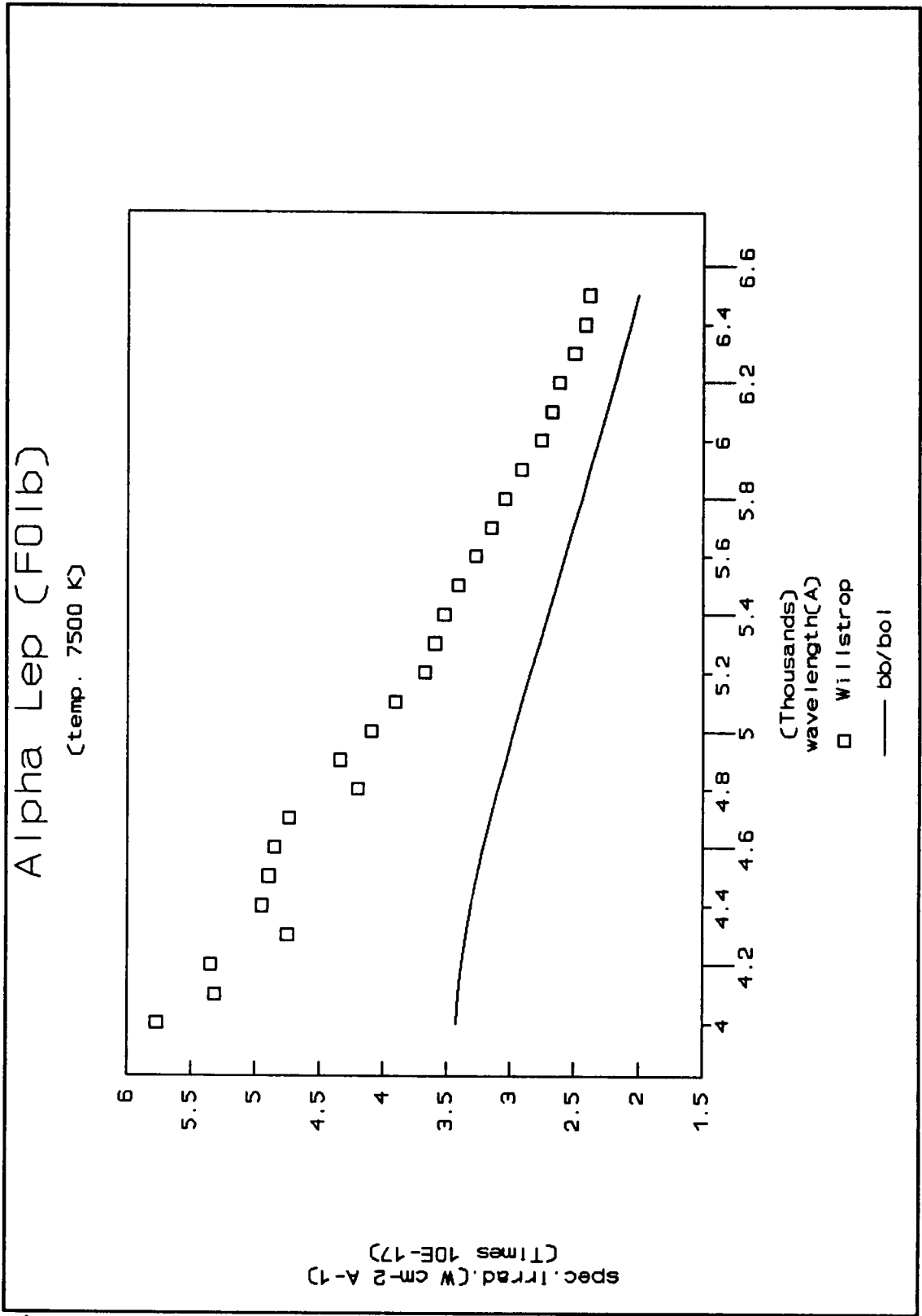


Figure B-9 Spectral Irradiance of Alpha Lep

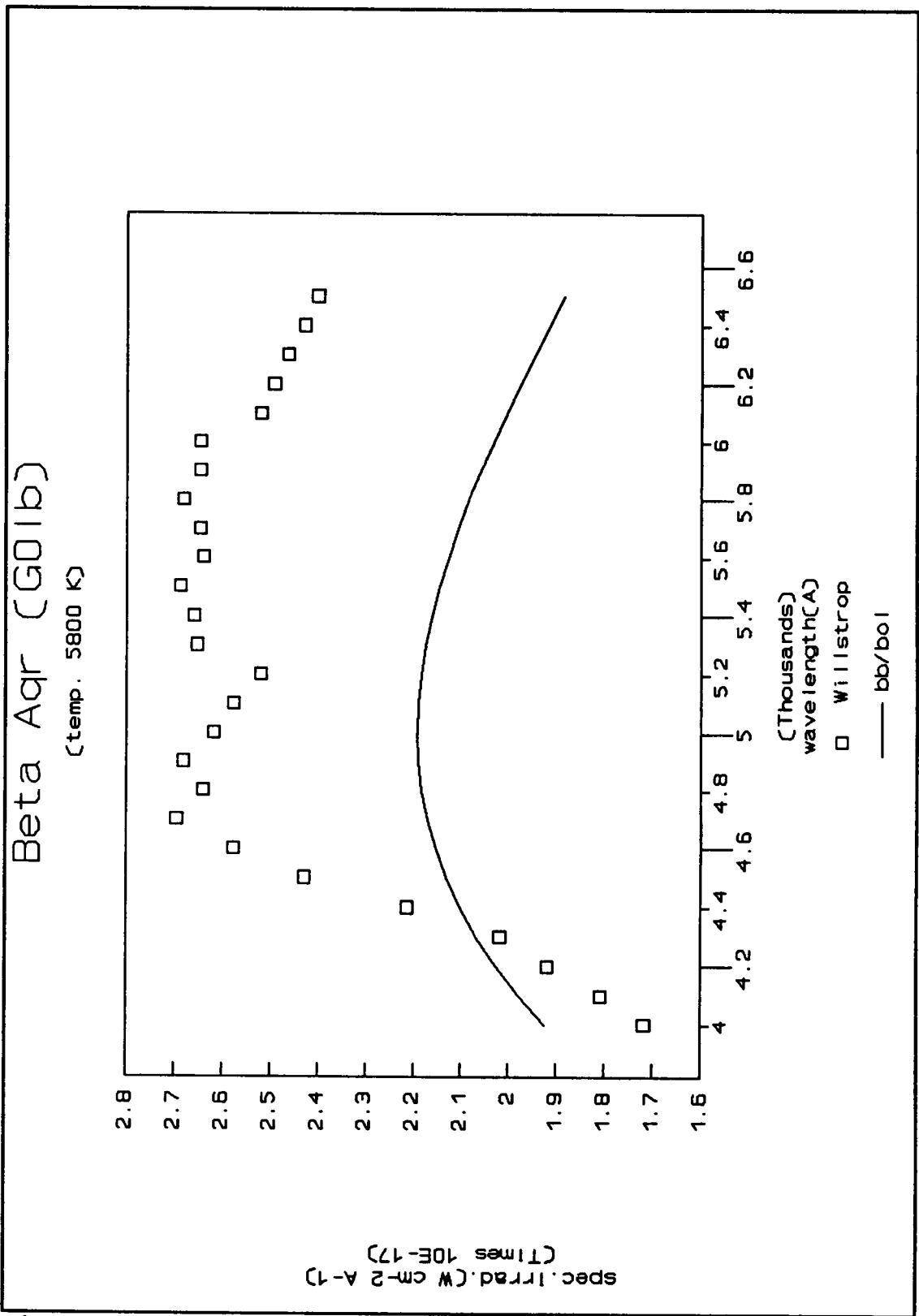


Figure B-10 Spectral Irradiance of Beta Aqr

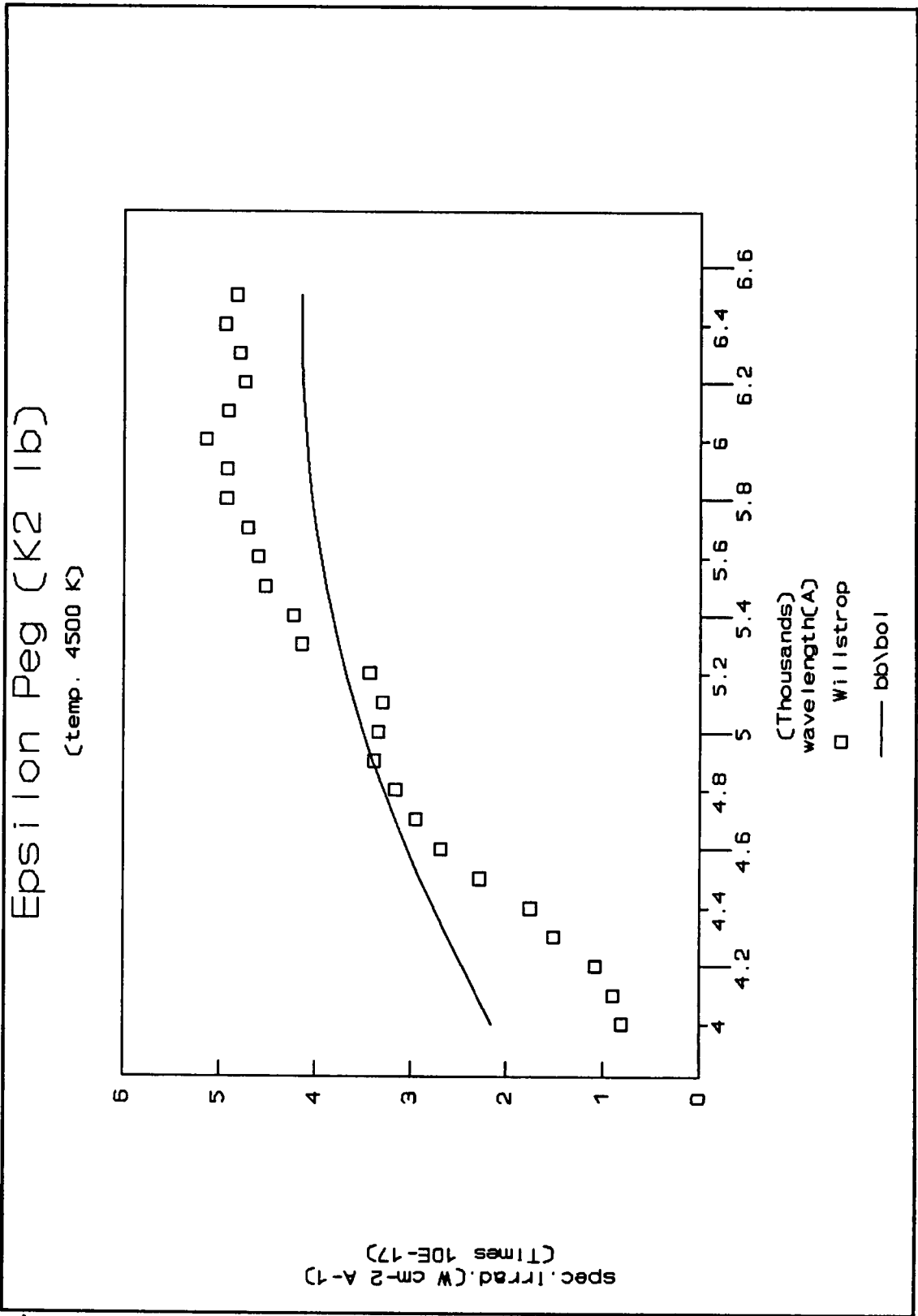


Figure B-11 Spectral Irradiance of Epsilon Peg

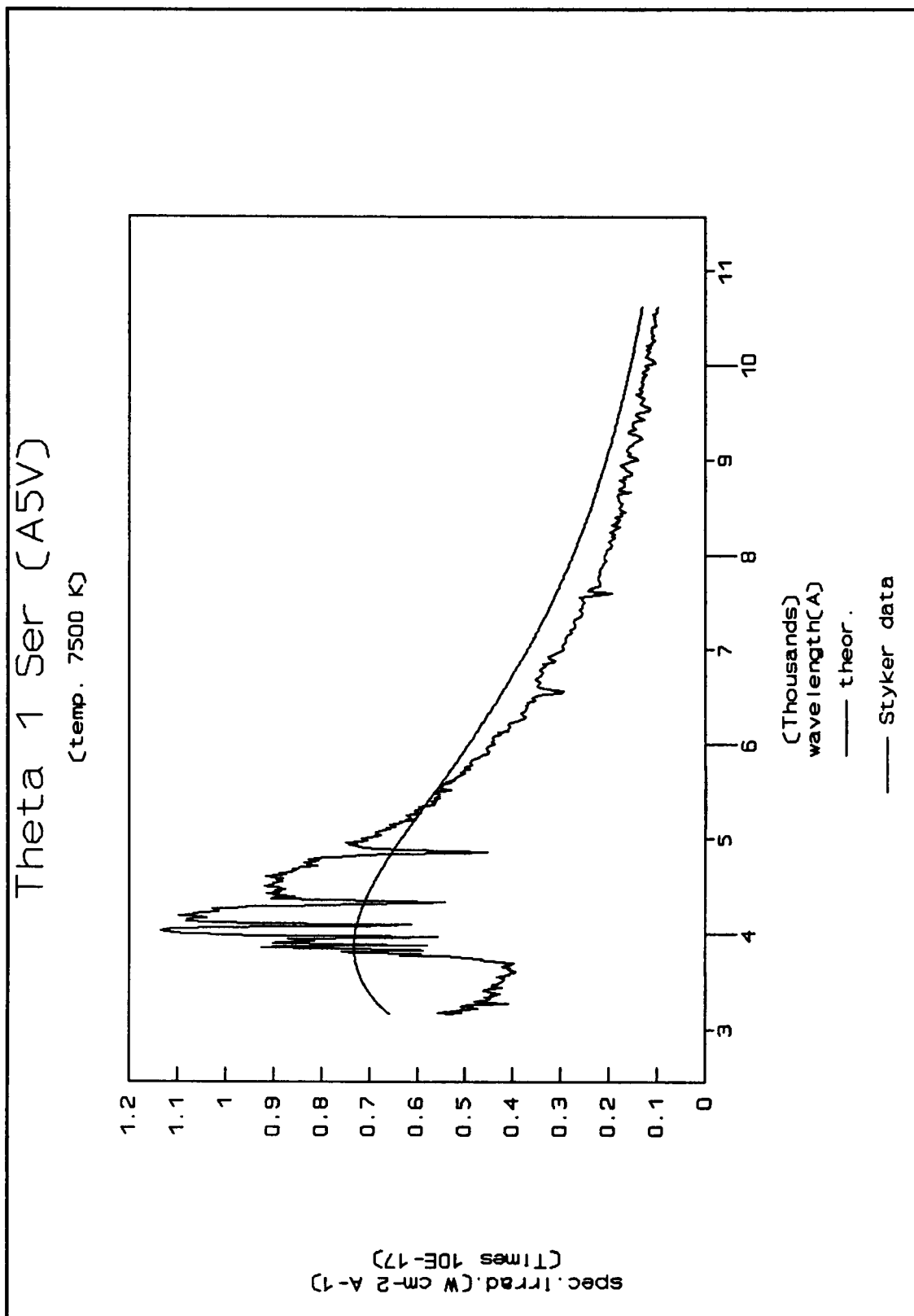


Figure B-12 Spectral Irradiance of Theta 1 Ser

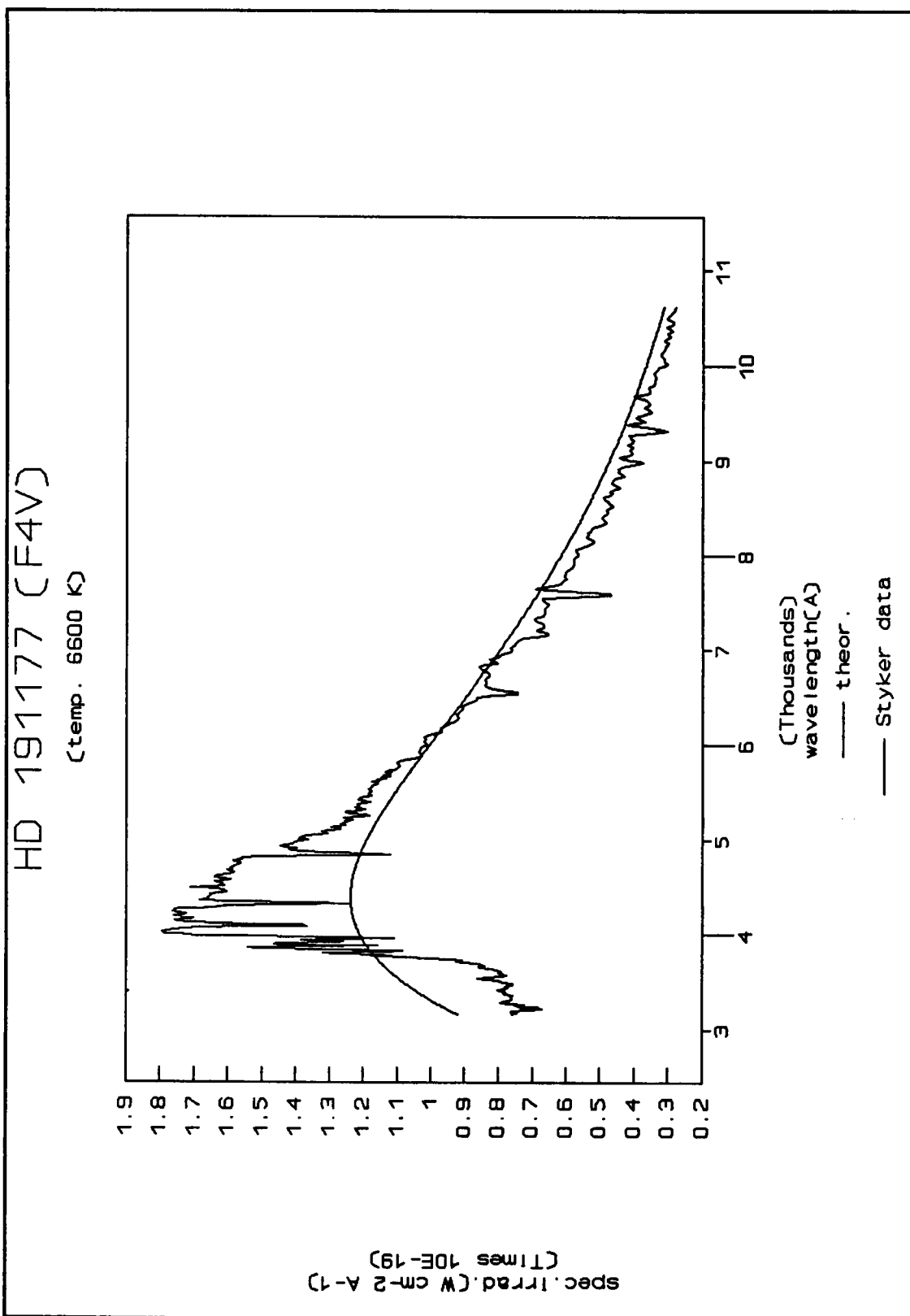


Figure B-13 Spectral Irradiance of HD 191177

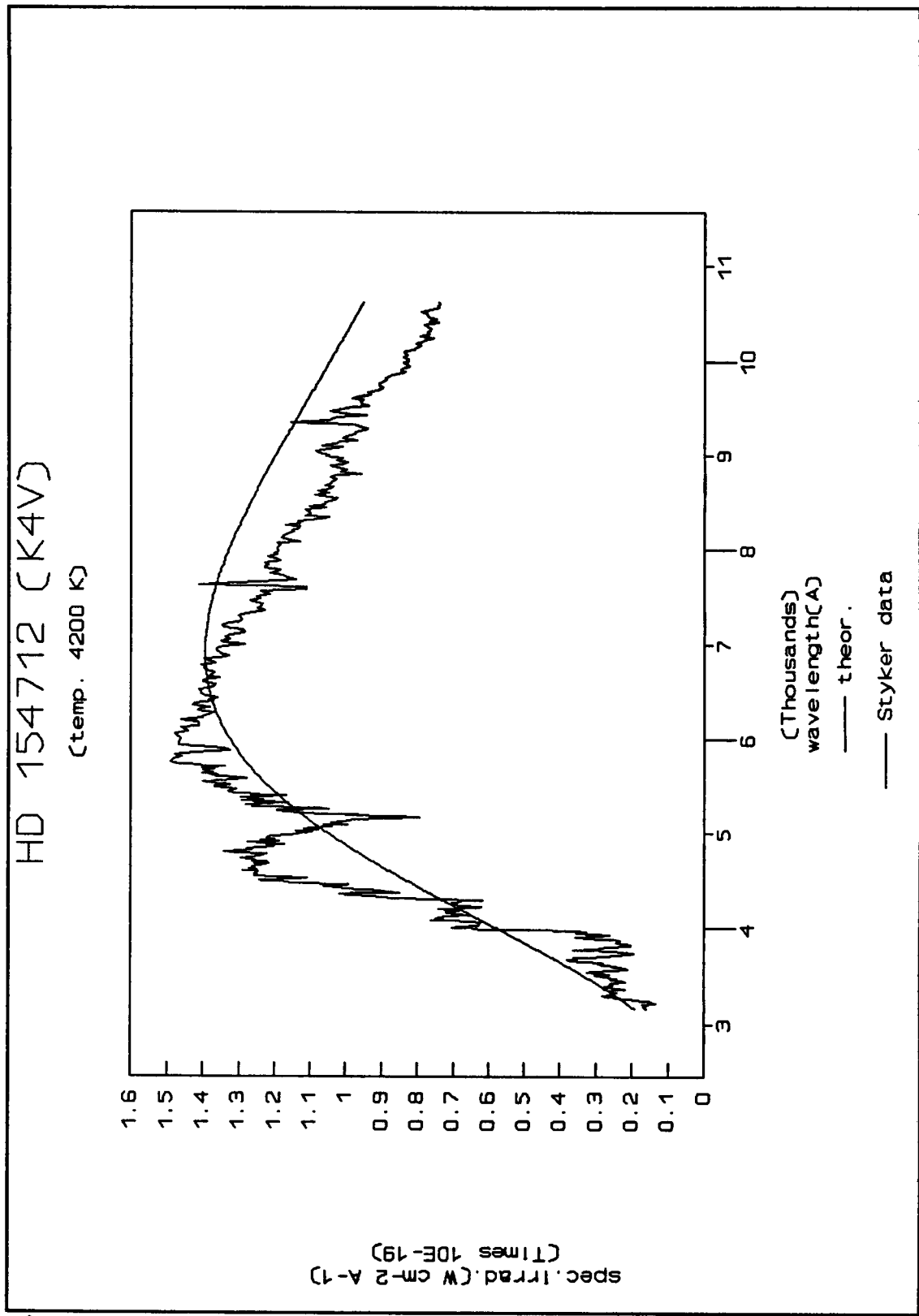


Figure B-14 Spectral Irradiance of HD 154712

Alpha Oph (A51111)

(temp. 8300 K)

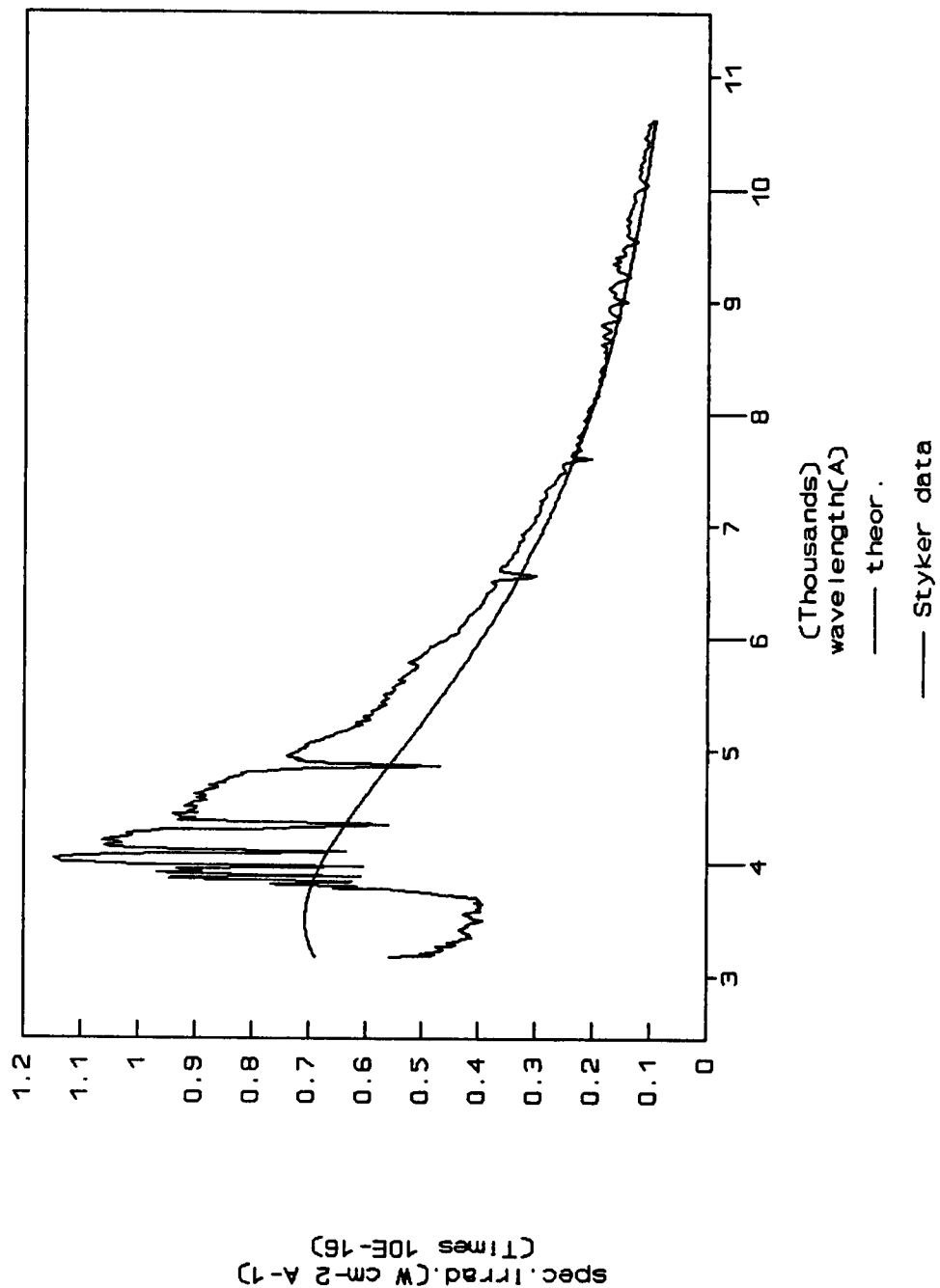


Figure B-15 Spectral Irradiance of Alpha Oph (Styker)

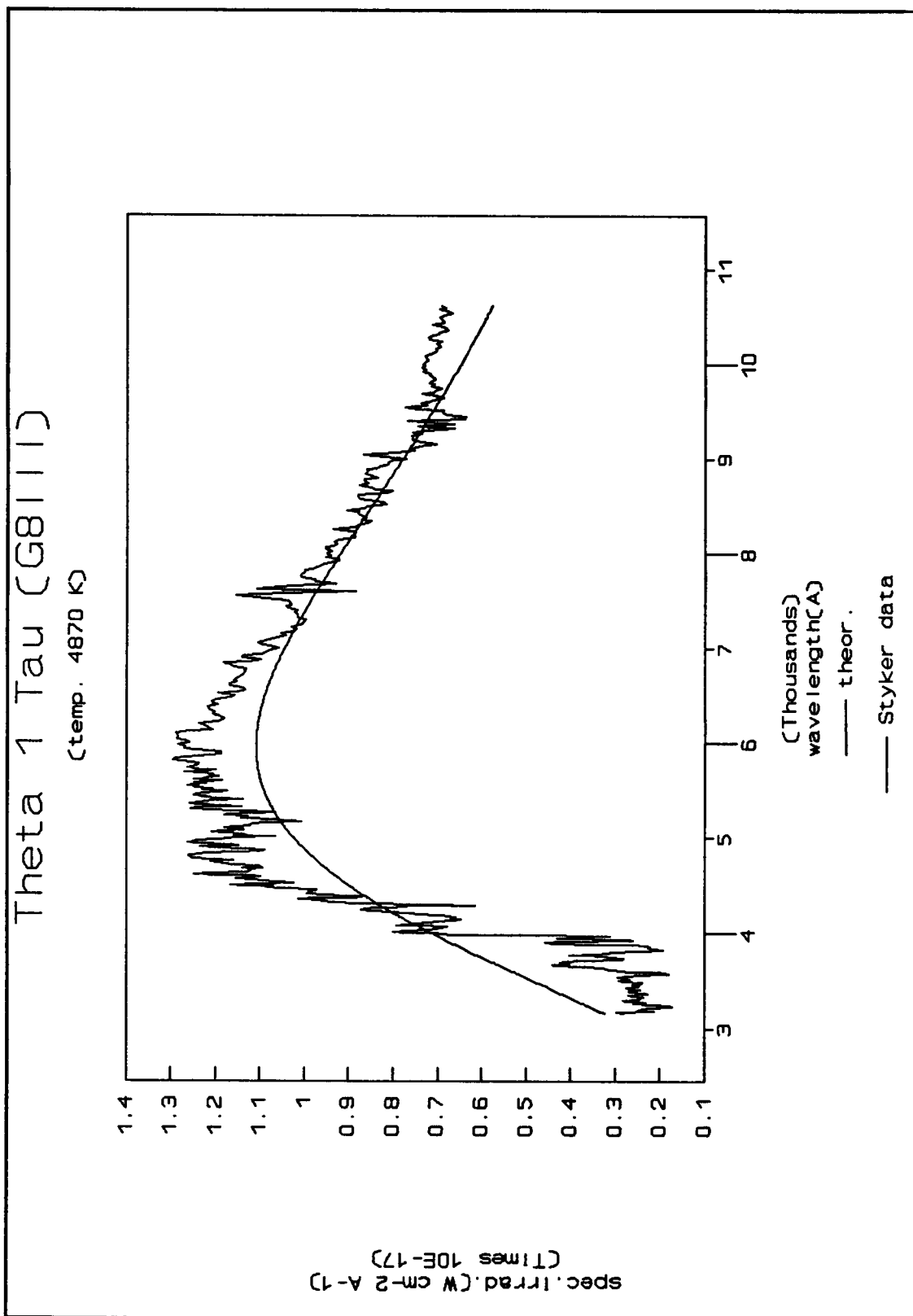


Figure B-16 Spectral Irradiance of Theta 1 Tau

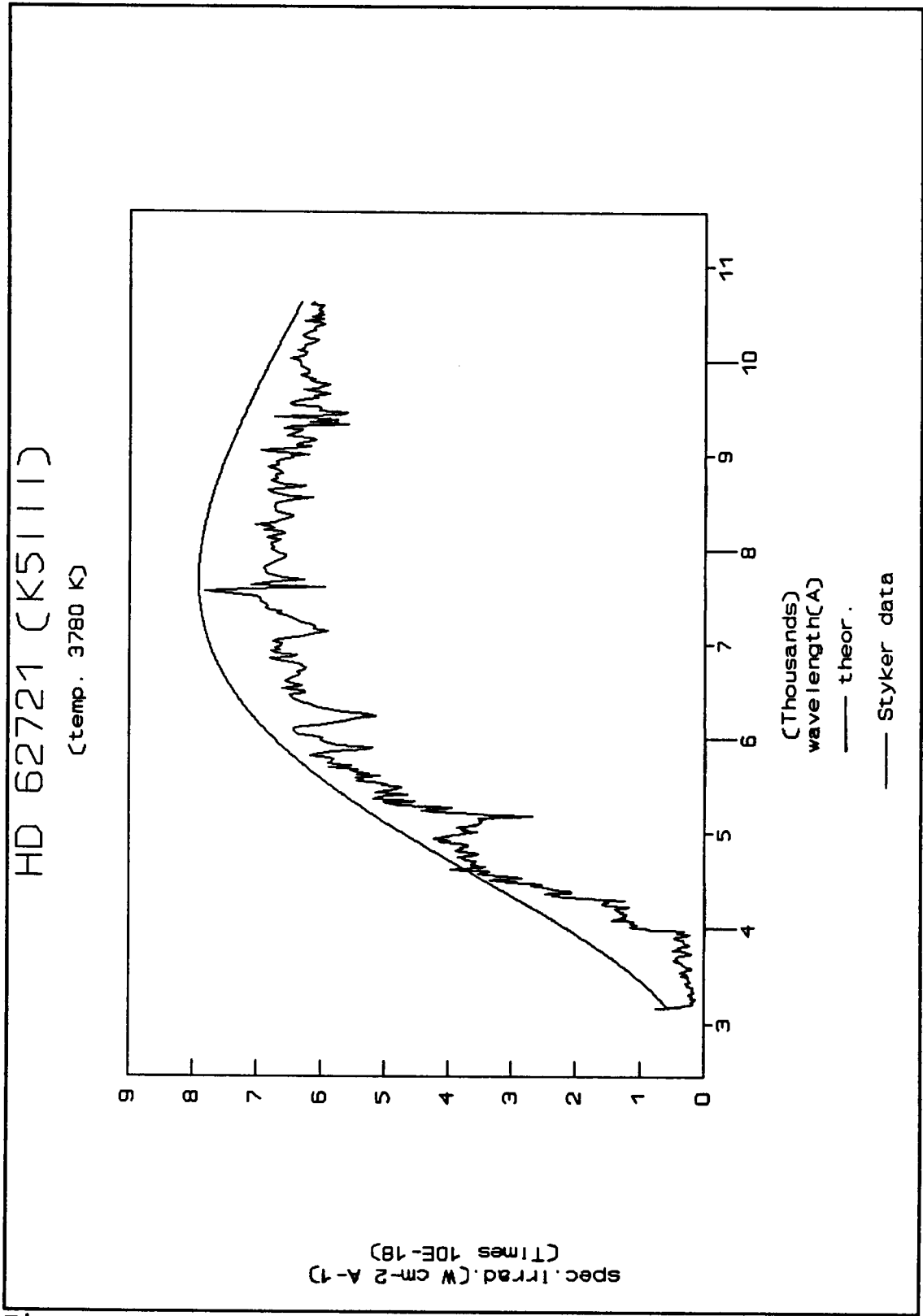


Figure B-17 Spectral Irradiance of HD 62721

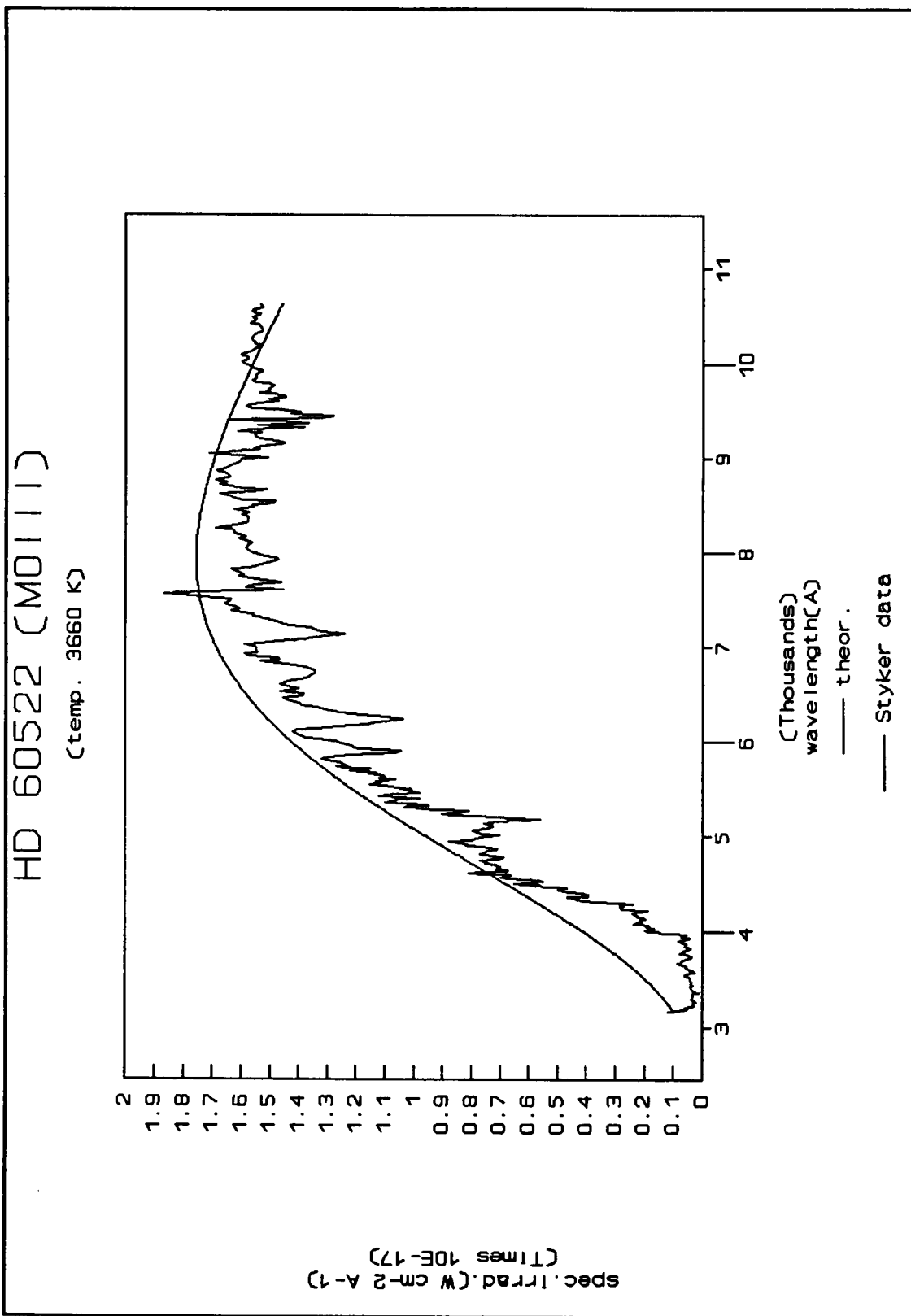


Figure B-18 Spectral Irradiance of HD 60522

Vita

Valinda Dee Kirkland was born in Birmingham, Alabama on June 13, 1968. She received elementary and high school education in Chelsea, Alabama and graduated from Chelsea High School in May, 1986. The following September she entered Samford University and in May, 1990 received the degree of Bachelor of Science in Physics and Mathematics. The following August she enrolled at the University of Tennessee Space Institute. She completed the degree of Masters of Science in Physics in December, 1992.