LINE BLANKETING MEASUREMENTS FOR THE STAR BETA CORONAE BOREALIS

By

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CHAPTER I

INTRODUCTION

In studying stellar spectra we must consider the fact that the continuum and line formation are interrelated. We, therefore, study the effects of spectrum lines upon the physical conditions in the stellar atmosphere. This, then is why the concept of line blanketing was introduced into astrophysics.

Historically, the concept of line blanketing was formulated by Milne in 1922. In the ensuing years other investigators have used the ideas behind the original concept for various problems such as the solar atmosphere and radiative transfer. Besides Milne, Chandrasekar, Münch and Athay and Skumanich have done considerable work and refinement on the original concept of line blanketing.

Milne (1922) assumed that the spectral lines are formed in an optically thin layer, the "reversing" layer, absorbing some radiation and then returning it back to the atmosphere. Since radiative equilibrium is assumed, the reflected radiation does not accumulate, but radiates as increased flux in the continuum between absorption lines because of the temperature increase in the atmosphere below the reversing layer.

Chandrasekhar (1935), on the other hand, assumed that the absorption lines are distributed uniformly over the entire spectral range and that they originated in the entire atmosphere. Chandrasekhar then solved the equation of transfer for the absorption lines and the continuum separately. Moreover, he showed that the temperature below the reversing layer increased.

Later, Münch (1946) solved the same problem as Chandrasekhar, but he used Gaussian sums in the evaluation of the source function and he generalized by assuming the absorption lines to be unevenly distributed over the spectrum.

In 1969, Athay and Skumanich considered wavelength and depth dependence of line blanketing effects for absorption and noncoherent scattering. A two-level atom was studied in detail and line and continuum interactions were considered through collisional processes.

Although these investigators and many others have refined Milne's original concepts much work remains to be done because no complete theory exists which can explain blanketing effects in stellar atmospheres.

Line blanketing usually refers to the presence of lines which effect both the distribution of the emergent flux with frequency and the temperature distribution of stellar atmospheres.

Line blanketing can be separated into three separate effects. The "blocking effect" occurs because radiation is simply blocked. This happens because one observes that the lines are darker than the adjacent continuum, and therefore, the flux emerging in a given band will be depressed. The blocking effect shifts a stars observed color. Therefore, care must be taken when comparing stars which have different line strengths. Wildey, Sandage, and the Burbridges (1962) have been instrumental in developing methods which take into account the blocking effect.

The second effect of line blanketing is "back warming" in the atmospheric layers near the photosphere. We compare atmospheres, one of which has strong lines and the other without strong lines. For our model we assume that each has the same total net flux escaping from the star. Obviously, very little flux is transported in the opaque lines, hence, most of the transport occurs in the continuum. Since we require the same total net flux for both atmospheres, the frequency band available to the continuum with lines is decreased; therefore, the flux per unit frequency interval must increase which implies an increase in the local temperature of the blanketed atmosphere relative to the unblanketed one.

The third effect is the altering of the boundary temperature of the stellar atmosphere. The boundary temperature change is a sensitive function of the mode of line formation and is theoretically very important.

We can consider a simple classical picture where the lines have a source function of the form

$$S = (1-\varepsilon)\ I_\nu J_\nu + \varepsilon\ I_\nu B_\nu$$

where ε is the parameter which delineates the partitioning between photons "absorbed" and those "scattered" coherently. B_ν in the Planck function; I_ν is the specific intensity of radiation; and J_ν is the emission coefficient (per gram of stellar material).

Then the condition for radiative equilibrium is

$$\int_0^\infty (\kappa_\nu + \sigma_\nu + I_\nu)\ J_\nu d_\nu = \int_0^\infty \kappa_\nu\ B_\nu\ d_\nu + \int_0^\infty \sigma_\nu\ J_\nu\ d_\nu + \varepsilon \int_0^\infty I_\nu\ B_\nu\ d_\nu$$

$$+ \ (1-\varepsilon) \int_0^\infty I_\nu\ J_\nu\ d_\nu. \tag{1-1}$$

$$\text{Or,} \int_0^\infty \kappa_\nu\ B_\nu\ d_\nu = \int_0^\infty \kappa_\nu\ J_\nu\ d_\nu + \varepsilon \int_0^\infty I_\nu\ (J_\nu - B_\nu)\ d_\nu, \tag{1-2}$$

where κ_ν is the absorption coefficient (per gram of stellar material), corrected for stimulated emissions and σ_ν is the scattering coefficient.

If we assume that the lines are very opaque then we can approximate $J_\nu = \frac{1}{2} B_\nu(T_o)$ at the boundary in the lines. Then,

$$\int_o^\infty \kappa_\nu B_\nu (T_o) d\nu = \int_o^\infty \kappa_\nu J_\nu d_\nu - \frac{\varepsilon}{2} \int_o^\infty I_\nu B_\nu (T_o) d_\nu . \qquad (1\text{-}3)$$

The presence of the lines, therefore, lowers the boundary temperature compared with the case of no lines. If $\varepsilon = 1$ (LTE) the effect is large, but is vanishingly small if $\varepsilon \to o$ which implies lines formed by scattering.

The argument is not complete because the change in J_ν has been ignored in the continuum. The transfer equiation must be solved for both lines and the continuum subject to equilibrium requirements. This has been done by Chandrasekhar (1936), Münch (1946), Mihalas and Morton (1965).

CHAPTER II

LINE BLANKETING MEASUREMENTS

As stated in Chapter I line blanketing or the blocking effect referred to the effect of the absorption lines on the temperature distribution of a stellar atmosphere. This blocking effect causes backwarming which raises the atmospheric temperature below the "reversing" layer and increases the flux. If we removed all the lines, the level of the continuum would decrease from F_1 to F_2 so that

$$\int_0^\infty F_2(\lambda)d\lambda = (1-\eta_T) \int_0^\infty F_1(\lambda)d\lambda, \qquad (2\text{-}1)$$

where η_T is the blanketing factor for all wavelengths. This in turn causes a change in the energy distribution which produces a color change. The UBV magnitudes due to backwarming can be described by the following relationship

$$\Delta M = 2.5 \log \frac{\int F_1(\lambda)\ S(\lambda)\ d\lambda}{\int F_2(\lambda)\ S(\lambda)\ d\lambda}, \qquad (2\text{-}2)$$

where $S(\lambda)$ is a photometrically dependent function.

We are concerned with the flux loss due to the lines in a given wavelength. The radiation from the star Beta Coronae Borealis is displayed in the form of an intensitometer tracing. The continuum is drawn directly on the tracing and γ, the blanketing coefficient, which is the ratio of the area under the intensitometer tracing, A, (see

Figure 1) to the area under the continuum, A + B, is obtained for a wavelength interval $\Delta\lambda$. This ratio is mathematically equivalent to

$$\gamma_\lambda = \int_\lambda^{\lambda+\Delta\lambda} F_\lambda d\lambda \Big/ \int_\lambda^{\lambda+\Delta\lambda} F_c d\lambda, \qquad (2\text{-}3)$$

where F_c is the continuum flux and F_λ is the observed flux. Then the blanketing factor which is $\eta_\lambda = 1 - \gamma_\lambda$ is determined.

In the calculation of model atmospheres line blanketing is important because one selects a model atmosphere which gives a suitable theoretical emergent flux. Since line blanketing is a measure of flux, and, this flux is due in part to the number of elements or their ions present in the stellar atmosphere, therefore, other calculations pertinent to the stars mass, surface gravity, temperature, and internal structure can be ascertained.

T_e, the stellar effective temperature may be calculated by

$$\sigma T_e^{\,4} = \sigma T_e'^{\,4} - \Delta F(0), \qquad (2\text{-}4)$$

where $\Delta F(0)$ is the flux absorbed by the lines and T_e' is a higher effective temperature due to back warming in our model.

If we let $F_\nu(\lambda)$ be the monochromatic flux per unit interval centered on λ and if $F_\nu(5560)$ is the standard for comparison, then we can define the monochromatic magnitudes as

$$\Delta m = -2.5 \log \frac{F_\nu(\lambda)}{F_\nu(5560)} . \qquad (2\text{-}5)$$

Then the blanketing-free monochromatic flux is

$$\Delta M^*(\lambda^{-1}) = \Delta M(\lambda^{-1}) + 2.5 \log (\gamma_\lambda/\gamma_o) \tag{2-6}$$

where γ_o is the average blanketing coefficient at 5560Å.

Other calculations are possible and further material may be found in the theses of Myrick (1970) and Hansen (1972).

For a historical background as well as a more physically rigorous exposition of model atmospheres and line blanketing Milne (1922), Chandrasekar (1935), Münch (1946), and Athay and Skumanich (1969) may be consulted.

CHAPTER III

OBSERVATIONAL DATA AND PROCEDURES FOR LINE BLANKETING MEASUREMENTS

The spectrograms from Beta Coronae Borealis, an A5p star (1900: $\alpha = 15^h23^m7^s$; $\delta = +29^\circ27'$; $m_v = 3.72$) were taken by Drs. Leon W. Schroeder and Ronald K. Oines both of Oklahoma State University and Dr. John C. Evans of Kansas State University at the Coude' focus of the 84-inch telescope at the Kitt Peak National Observatory during June, 1971. It is operated by the Association of Universities for Research in Astronomy, Inc., under the auspices of the National Science Foundation. Each spectrogram is about 1500Å wide and was exposed on 28 inches of photographic plate (2 10-inch strips and 1 8-inch strip). The dispersion was about 2.2 Å/mm in the second order blue.

Intensity tracings were made by Dr. Leon W. Schroeder (June 1971) and by Thomas M. Jordan (May, 1972) with the Hilger-Watts Direct Intensity Recording Microphotometer, Model L-470 at Kitt Peak National Observatory headquarters in Tucson, Arizona. The carriage speed for the tracings was 0.5 millimeter/minute while the plate-to-chart magnification was 102.5/1. Table I lists data pertinent to the microphotometer tracings.

The determination of the blanketing coefficient requires the measurement of the area enclosed by the continuum, A + B, over the 10Å interval, and the area below the line profiles on the intensitometer tracing, B. An OTT-Rolling Disk Planimeter was used to measure the areas involved, A. A clockwise movement (right to left) of the plani-

TABLE I

PLATE AND MICROPHOTOMETER DATA

Kitt Peak Plate and Tracing Number	Wavelength Range (Angstroms)	Tracing Made by*
D2829a-1	$\lambda\lambda$3690-4180	TMJ
D2829a-2	$\lambda\lambda$4190-4780	LWS
D2829a-3	$\lambda\lambda$4790-4940	TMJ
D2837a-1	$\lambda\lambda$3520-3680	TMJ

*TMJ = Thomas M. Jordan

LWS = Leon W. Schroeder

meter's tracing point over the curves. The line blanketing coefficient is then determined as $\gamma = \frac{B}{A+B}$.

The planimeter readings were recorded with a setting of 44.00 on the planimeter arm. The ratios were then calculated using the conversion factor 1.600924 $\frac{in^2}{\text{planimeter unit}}$.

The 10-Å intervals on the tracings were determined by the equation $D = \frac{\Delta\lambda}{d}$, where D is the interval length in inches, $\Delta\lambda$ is the difference in wavelengths in angstroms and d is the dispersion in Å/in. The average dispersion was approximately 0.560 $\frac{\text{Å}}{\text{in}}$ and most of these calculations were provided by Mr. Thomas Jordan.

Figure 1 is a sample intensitometer tracing depicting a 10-Å interval with the continuum drawn in along with what the areas A and B represent and how γ was then determined.

Figure 2 is a plot of the dispersion which was determined as described in the text. The line through the points is the mean of the dispersion and was extrapolated from λλ4900-4950.

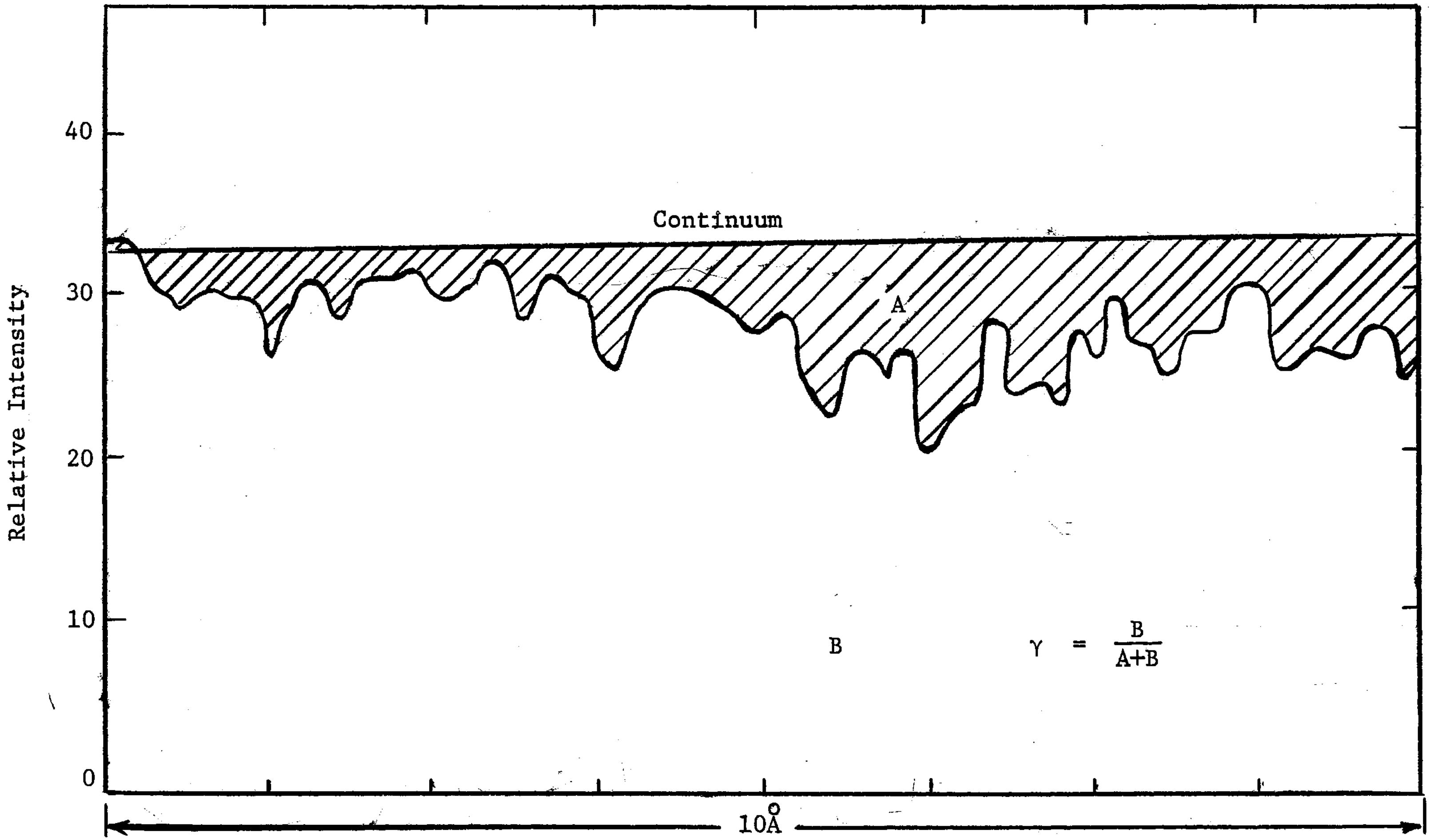

Figure 1. Sample Intensitometer Tracing Showing Method of Determining γ

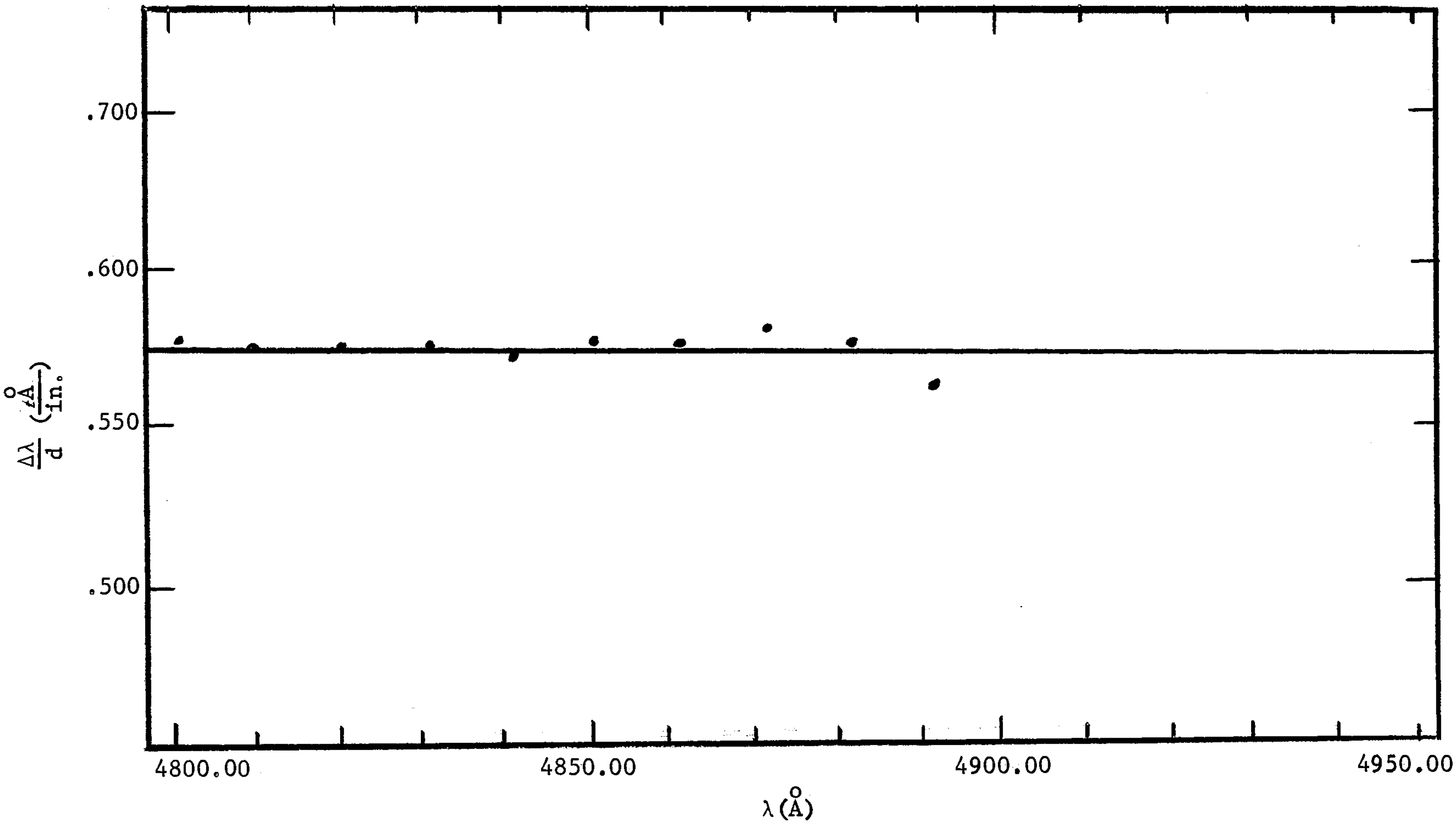

Figure 2. Dispersion for λλ4800-4950--Tracing No. D2829a-3

CHAPTER IV

RESULTS AND CONCLUSIONS

The line-blanketing coefficients for the star Beta Coronae Borealis were obtained. The values are listed in Table II along with the reciprocal wavelength in microns and the blanketing factor.

Column 1 lists the wavelength in Å at the lower limit of each 10Å interval. Column 2 gives the reciprocal wavelength in microns. Column 3 lists the number of tracings used. Column 4 lists the blanketing coefficient, γ. Column 5 lists the blanketing factor, η.

Note that "missing" regions in the tabulation of Table II occur at regions where sections of the plate butt together.

Figure 3 is a representative plot of blanketing factors which are tabulated in column 5 of Table II. The blanketing factors have been graphed for the region $\lambda\lambda$4000-4100.

Calculations of γ have been based on the assumptions that the continuum has been properly located and that the elements have been properly identified allowing the 10-Å intervals to be located. Errors then occur because the continuum is not located with the greatest of certainty and perhaps in some instances line identification is not exact. If several tracings had been used and an average obtained the blanketing factors may have been ascertained with much greater confidence as to their values. Later researchers may then use the values tabulated in Table II as a comparison.

TABLE II

BLANKETING COEFFICIENTS (10-Å INTERVALS) λλ3520-4940

λ	λ^{-1}	Number of Tracings	γ	η	
3520	2.841	1	0.559	0.441	
3530	2.833	1	0.561	0.439	
3540	2.825	1	0.576	0.424	
3550	2.817	1	0.574	0.426	
3560	2.809	1	0.597	0.403	
3570	2.801	1	0.561	0.439	D2837a(1)
3580	2.793	1	0.531	0.469	
3590	2.785	1	0.582	0.418	
3600	2.778	1	0.547	0.453	
3610	2.770	1	0.543	0.457	
3620	2.762	1	0.578	0.422	
3630	2.755	1	0.549	0.451	
3640	2.747	1	0.580	0.420	
3650	2.740	1	0.505	0.495	
3660	2.732	1	0.438	0.562	
3670	2.725	1	0.436	0.564	
3680	2.717	1	0.412	0.588	
3690	2.710	1	0.417	0.583	D2829a(1)
3700	2.703	1	0.407	0.593	Part I
3710	2.695	1	0.404	0.596	
3720	2.688	1	0.414	0.586	
3730	2.681	1	0.390	0.610	
3740	2.674	1	0.437	0.563	
3750	2.667	1	0.450	0.551	
3760	2.660	1	0.445	0.555	
3770	2.653	1	0.460	0.540	
3780	2.646	1	0.593	0.407	
3790	2.639	1	0.388	0.612	
3800	2.632	1	0.543	0.457	
3810	2.625	1	0.620	0.380	
3820	2.618	1	0.608	0.392	
3830	2.611	1	0.337	0.663	
3840	2.604	1	0.553	0.447	
3850	2.597	1	0.647	0.353	
3860	2.591	1	0.695	0.305	
3870	2.584	1	0.608	0.392	
3880	2.577	1	0.412	0.588	
3890	2.571	1	0.456	0.544	
3900	2.564	1	0.620	0.380	
3910	2.558	1	0.661	0.339	
3920	2.551	1	0.644	0.356	

TABLE II (Continued)

λ	λ^{-1}	Number of Tracings	γ	η
3930	2.545	1	0.408	0.592
3940	2.538	1	0.636	0.364
3950	2.532	1	0.601	0.399
3960	2.525	1	0.375	0.625
3970	2.519	1	0.411	0.589
3980	2.513	1	0.626	0.374
3990	2.506	1	0.691	0.309
4000	2.500	1	0.824	0.176
4010	2.494	1	0.779	0.221
4020	2.488	1	0.810	0.190
4030	2.481	1	0.765	0.235
4040	2.475	1	0.744	0.256
4050	2.469	1	0.718	0.282
4060	2.463	1	0.715	0.285
4070	2.457	1	0.625	0.375
4080	2.451	1	0.628	0.372
4090	2.445	1	0.498	0.502
4100	2.439	1	0.372	0.628
4110	2.433	1	0.585	0.415
4120	2.427	1	0.619	0.381
4130	2.421	1	0.679	0.321
4140	2.415	1	0.717	0.283
4150	2.410	1	0.706	0.294
4160	2.404	1	0.759	0.241
4170	2.398	1	0.666	0.334
4180	2.392		Missing	Missing
4190	2.386	2	0.738	0.262 D-2829a
4200	2.381	2	0.761	0.239
4210	2.375	1	0.768	0.232
4220	2.369	1	0.777	0.223
4230	2.364	1	0.795	0.205
4240	2.358	1	0.807	0.193
4250	2.352	1	0.773	0.227
4260	2.347	1	0.820	0.180
4270	2.341	1	0.820	0.180
4280	2.336	1	0.819	0.181
4290	2.331	1	0.778	0.222
4300	2.326	1	0.738	0.262
4310	2.320	1	0.804	0.196
4320	2.315	1	0.733	0.267
4330	2.309	1	0.533	0.467
4340	2.304	1	0.487	0.513
4350	2.299	1	0.682	0.318
4360	2.294	1	0.782	0.218
4370	2.288	1	0.838	0.162
4380	2.283	1	0.785	0.215
4390	2.278	1	0.822	0.178

TABLE II (Continued)

λ	λ^{-1}	Number of Tracings	γ	η	
4400	2.272	1	0.837	0.163	
4410	2.268	1	0.839	0.161	
4420	2.262	1	0.847	0.152	
4430	2.257	1	0.829	0.171	
4440	2.252	1	0.846	0.154	
4450	2.247	1	0.824	0.176	
4460	2.242	1	0.789	0.211	
4470	2.237	1	0.852	0.147	
4480	2.232	1	0.791	0.209	
4490	2.227	1	0.845	0.151	
4500	2.222	1	0.859	0.141	
4510	2.217	1	0.852	0.148	
4520	2.212	1	0.764	0.236	
4530	2.208	1	0.817	0.183	
4540	2.203	1	0.799	0.201	
4550	2.198	1	0.781	0.219	
4560	2.193	1	0.827	0.173	
4570	2.188	1	0.835	0.165	
4580	2.183	1	0.757	0.243	
4590	2.179	1	0.794	0.206	
4600	2.174	1	0.838	0.162	
4610	2.169	1	0.822	0.178	
4620	2.164	1	0.855	0.145	
4630	2.159		Missing	Missing	
4640	2.155		Missing	Missing	
4650	2.151	1	0.778	0.222	
4660	2.146	1	0.792	0.208	
4670	2.141	1	0.813	0.187	
4680	2.137	1	0.826	0.174	
4690	2.132	1	0.796	0.204	
4700	2.128	1	0.796	0.204	
4710	2.123	1	0.810	0.190	
4720	2.119	1	0.822	0.178	
4730	2.114	1	0.819	0.181	
4740	2110	1	0.823	0.177	
4750	2.105	1	0.826	0.174	
4760	2.101	1	0.812	0.188	
4770	2.096	1	0.849	0.151	
4780	2.092	1	0.821	0.179	
4790	2.088	1	0.885	0.115	2829a(3)
4800	2.083	1	0.911	0.089	Part I
4810	2.079	1	0.904	0.096	
4820	2.075	1	0.871	0.128	
4830	2.070	1	0.840	0.160	
4840	2.066	1	0.690	0.310	
4850	2.062	1	0.560	0.440	
4860	2.058	1	0.455	0.545	
4870	2.053	1	0.655	0.345	

TABLE II (Concluded)

λ	λ^{-1}	Number of Tracings	γ	η
4880	2.049	1	0.699	0.301
4890	2.045	1	0.750	0.250
4900	2.041	1	0.770	0.230
4910	2.037	1	0.707	0.293
4920	2.033	1	0.660	0.340
4930	2.028	1	0.637	0.363
4940	2.024	1	0.629	0.371

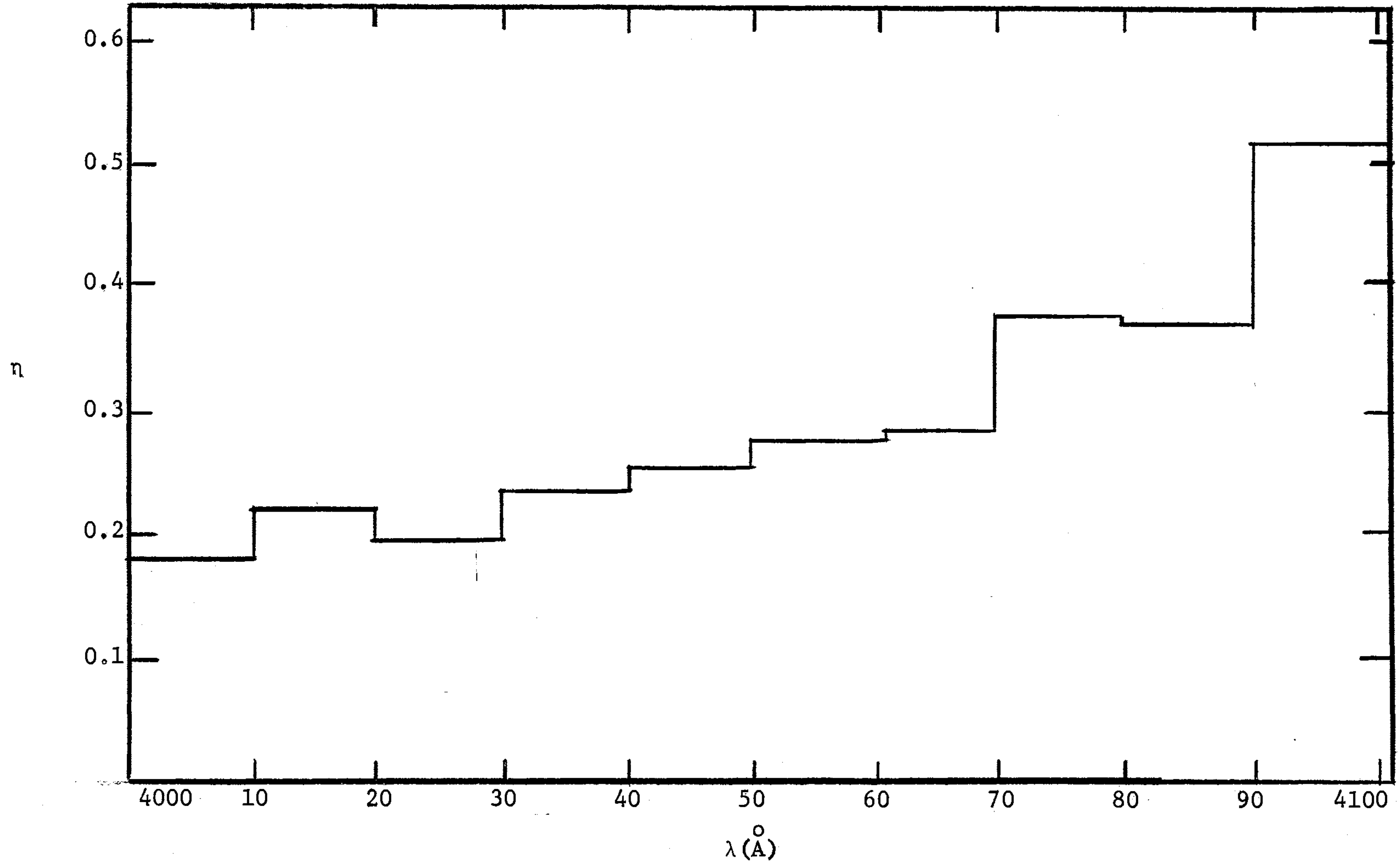

Figure 3. Blanketing Factor for Beta Coronae Borealis in the Region λλ4000-4100

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