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COLOUR INDICES OF FLARE STARS AND THE INVERSE COMPTON-EFFECT

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SUMARIO

Gurzadyan (1965, 1968) ha propuesto que las ráfagas de estrellas enanas tardías se deben a la aparición espontánea de electrones rápidos sobre la fotosfera de la estrella. Estos electrones interaccionan con los fotones térmicos por medio del efecto Compton inverso y así parte de los fotones infrarrojos pasan a longitudes de onda ultravioletas. Se ha preparado un diagrama color-color teórico basado en las hipótesis anteriores. Se compara este diagrama con los colores observados de las estrellas ráfaga del tipo UV Cet, estrellas T Tauri, y estrellas ráfagas en Orión. Se demuestra que las estrellas T Tauri están en un estado permanente de actividad ráfaga esencialmente al mismo nivel de actividad. NX Mon es un ejemplo típico de actividad ráfaga permanente. Se establece la siguiente secuencia evolutiva:

Estrellas del tipo NX Mon → estrellas T Tauri ordinarias → estrellas ráfaga del tipo UV Cet

Teóricamente se predice que *U—B* puede alcanzar valores de —1ᵐ6 para el caso del efecto Compton inverso.

ABSTRACT

According to Gurzadyan (1965, 1968) the flare of cold dwarf stars is due to the spontaneous appearance of fast electrons over the stellar photosphere. Through an inverse Compton-effect between these electrons and the thermal photons part of the infrared radiation is changed into ultraviolet. A theoretical colour-colour diagram is developed for such a non-thermal radiation. A comparison of this diagram with the observed colours of UV Cet type flare stars, T Tauri stars and flare stars in Orion is carried out. It is shown that the T Tauri stars are in a permanent flaring state with a nearly constant degree of activity. NX Mon is a typical example of very intense permanent flare activity. The following evolutionary sequence is established:

NX Mon type stars → Ordinary T Tauri stars → UV Cet flare stars

The predicted value of *U—B* in the case of inverse Compton-effect can reach —1ᵐ6.

According to Gurzadyan (1965, 1968) the flare of late-type dwarf stars is due to the spontaneous appearance over their photosphere of fast electrons, with an energy slightly exceeding their rest energy (the hypothesis of "fast electrons"). The interaction of those electrons with thermal photons, i. e. the inverse Compton-effect, converts part of the infrared photons of the normal stellar photospheric radiation to shorter wavelengths causing not only an intensification of the ultraviolet end of the spectrum but also a change of the visible intensity of the object. The theory enables us to find the quantitative dependence of colour indices on the flare intensity. The present paper is aimed at comparing the theoretical colour indices, derived from the hypothesis of "fast electrons", with their observable quantities.

The continuous radiation intensity I_ν (μ, τ, T) at the frequency ν during the flare is given by the following expression (Gurzadyan 1968):

$$I_\nu (\mu, \tau, T) = B_\nu (T)\, C_\nu (\mu, \tau, T), \tag{1}$$

where B_ν (T) is Planck's intensity at the effective temperature T of the stellar photosphere in its normal state, i. e. when the star is not experiencing any flare; and C_ν (μ, τ, T) is a dimensionless quantity, indicating the distortion (the increase in the UV and decrease in the IR) of the radiation intensity during the flare as compared to Planck's intensity of the unperturbed star. This function depends, in particular, on the stellar temperature and the form of the energy spectrum of the fast electrons.

In the case of monoenergetic electrons, when the common energy of all the electrons in the layer is $\mu = E/mc^2$, the function C_ν (μ, τ, T) assumes the form (see Gurzadyan 1968):

$$C_\nu (\mu, \tau, T) = E_4 (\tau) + \frac{3}{2\mu^4} \frac{e^x - 1}{e^{x/\mu^2} - 1} F_1 (\tau), \tag{2}$$

$$E_4 (\tau) = 3 \int_1^\infty e^{-\tau x} \frac{dx}{x^4}; \tag{3}$$

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$$F_1(\tau) = \int_1^\infty f_1(\tau, y)\,\frac{dy}{y^3}\ ; \qquad (4)$$

$$f_1(\tau, \theta) = \int_0^\tau E_3(t)\, e^{-(\tau - t)\sec\theta} \sec\theta\ dt\ ; \qquad (5)$$

$$E_3(\tau) = \int_1^\infty e^{-\tau x}\,\frac{dx}{x^3} \qquad (6)$$

where $x = h\nu/kT$, while τ is the effective optical thickness of the layer of fast electrons to the processes of Thomson scattering.

$$\tau = \sigma_e \int n dz = \sigma_e N\ ,$$

where N is the number of fast electrons over a column of 1 cm^2; and as a matter of fact, τ characterizes the theoretical power of the flare. The numerical values of the functions are given in Appendices A and B for a wide range of values of τ; the computations are made for the value $\mu^2 = 10$ (corresponding to the energy of fast electrons E $\approx 1.5 \times 10^6$ ev); the best agreement of the theory with the observations is obtained when $\mu^2 \sim 10$.

The theoretical colour-indices of flare stars, i. e. for the system "star + Compton radiation", are calculated by the formulae:

$$B - V = -2.5\ C_y + 1.04\ ; \qquad (7)$$

$$U - B = +2.5\ C_u - 1.12\ , \qquad (8)$$

where

$$C_y = \log\left[\int I_\nu(\mu, \tau, T)\, B_\lambda d\lambda \,/\, \int I_\nu(\mu, \tau, T)\, V_\lambda d\lambda\right] \qquad (9)$$

$$C_u = \log\left[\int I_\nu(\mu, \tau, T)\, B_\lambda d\lambda \,/\, \int I_\nu(\mu, \tau, T)\, U_\lambda d\lambda\right] \qquad (10)$$

and the function I_ν (μ, τ, T) is taken from (1), while U_λ, B_λ and V_λ are the relative sensitivities in the system *UBV* of Johnson and Morgan (1953).

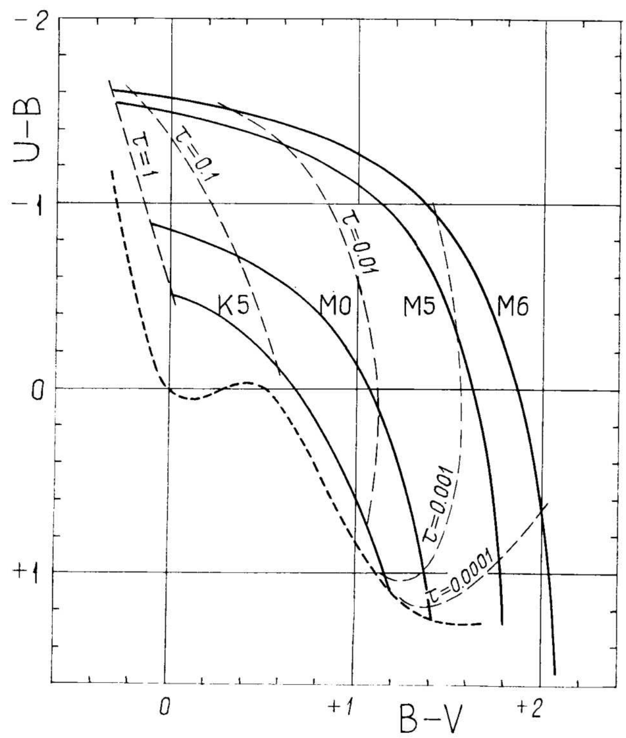

Fig. 1.—*Theoretical colour-colour diagram (solid lines) in the case of "Fast Electron" hypothesis.*

TABLE 1

Theoretical colour-indices U—B *and* B—V *during the flare of stars of M6, M5 and M0 type for the case of monoenergetic electrons with* $\mu^2 = 10$

Temperature of the star		*τ* 1	0.1	0.01	0.001	0.0001	0
2600° K (M6)	*U—B*	-1^m60	-1^m60	-1^m52	-0^m95	$+0^m48$	$+1^m57$
	B—V	−0.29	−0.21	+0.27	+1.42	+1.99	+2.10
2800° K (M5)	*U—B*	−1.63	−1.60	−1.38	−1.37	+0.80	+1.18
	B—V	−0.29	−0.13	+0.63	+1.55	+1.79	+1.82
3600° K (M0)	*U—B*	−1.65	−1.47	−0.67	+0.21	+0.43	+0.45
	B—V	−0.23	+0.24	+1.01	+1.26	+1.29	+1.30

Table 1 provides the numerical values *U—B* and *B—V* derived from the above formulae for stars M6, M5 and M0 (corresponding to effective temperatures 2600°, 2800° and 3600° K) and for different values of the flare power τ. Figure 1 contains the *(U—B, B—V)* dependence plotted from the values of Table 1. Corrections have been applied in order that the normal stars have the main sequence colors; for instance, for $\tau = 0$, an M0 star has $U-B = +1^m21$ and $B-V = +1^m48$ (Johnson and Morgan 1953). All the curves *(U—B, B—V)* virtually originate from the main sequence (dashed line) where $\tau = 0$. As τ increases, i. e. as the power of the flare grows, the colors change accordingly, deviating more from their main sequence position. The lines of equal τ are marked in the diagram.

The large separation from the main sequence of the curves for the M6 and M5 stars is significant, the increase in *(U—B)* becoming as large as 2^m5. It is remarkable that for the inverse Compton-effect the theoretical value of *U—B* becomes -1^m6 (for $\mu^2 = 10$) and even -1^m8 (for $\mu^2 = 50$). It should be noted in this connection that in the case of the hypothesis of "hot gas" the "ceiling" in *U—B* is equal to -0^m94 (Gershberg 1965), appreciably less than the value here derived. Thus the inverse Compton-effect qualitatively and quantitatively originates a completely new form of *(U—B, B—V)* diagram. Even crude estimates of the colour indices during flare up or during the variation of a star suspected of non-thermal radiation, are sufficient to determine whether this radiation is related to the phenomenon of the inverse Compton-effect or not.

Now we proceed to the comparison of the theoretical results obtained with the data observed for three classes of objects: UV Cet flare stars, T Tauri stars and flare stars in Orion.

1. Flare stars of the UV Cet type. Synchronous three-colour observations of bursts in the case of flare stars in the vicinity of the Sun (UV Cet type) are comparatively few in number. All the cases known to us have been compiled in Table 2. The data collected by Kunkel (1968) from a great number of bursts of AD Leo, YZ CMi and Wolf 359 would be of great interest due to their

TABLE 2

Observed colour indices U—B *and* B—V *at the maximum burst for a number of flare stars*

Star	*Date of flare*	*Flare amplitude* U	*Previous to flare* (U—B)*	(B—V)*	*At maximum flare* U—B	B—V	*Reference*
AD Leo	9.III.1959	1^m5	1^m06	$+1^m54$	-0^m14	$+1^m34$	Abell 1959
EV Lac	2.VIII.1967	1.55	(+1.2)	+1.38	−0.08	+1.34	Chugaynov 1970
EV Lac	31.VIII.1967	1.95	"	"	−0.55	+1.27	"
EV Lac	8.IX.1967	1.50	"	"	−0.10	+1.18	"
EV Lac	18.VIII.1968	3.1	"	"	−1.08	+0.80	Christaldy *et al.* 1969
HII 1306	1957	3.7	(+1.2)	(+1.4)	−1.07	+0.50	Johnson *et al.* 1958
DH Car	25.III.1968	1.0	+0.32	+0.90	−0.05	+0.44	Tapia 1968
S 5114	8.III.1969	4.1	+0.81	+1.64	−1.34	+0.62	Mumford 1969

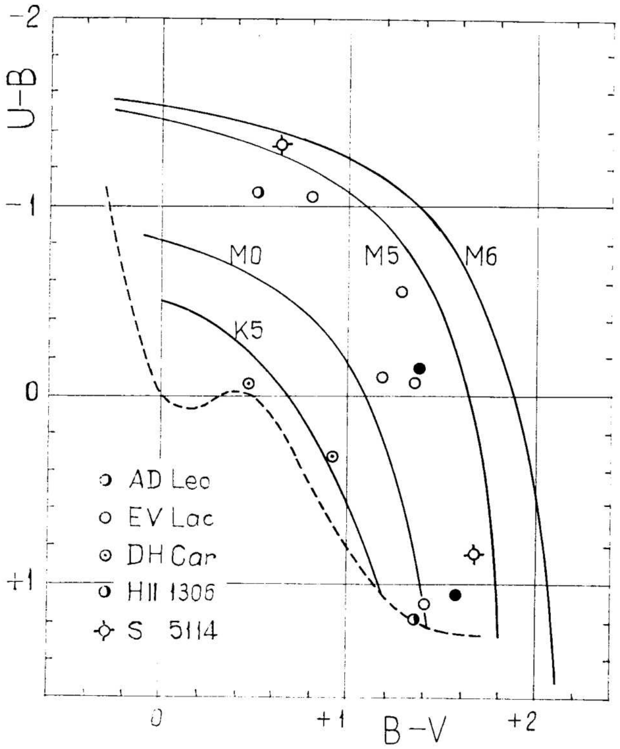

Fig. 2.—*The flare stars of UV Cet type on the theoretical colour-colour diagram.*

uniformity; unfortunately they contain only the colour indices of the additional radiation i. e. the values $(U-B)_f$ and $(B-V)_f$ without indicating the amplitude of the bursts; therefore we cannot use these data here. Figure 2 presents the theoretically predicted *(U—B, B—V)* diagram and the observed data given in Table 2. In the lower end of the diagram are located the stars in their normal state. During the flare up their position moves upward and to the left in the diagram; the more powerful the flare is, the higher they rise. For instance, during the flare of S 5114 the observed *U—B* reached -1^m34 (!). These comparisons show that the colour indices observed during the flare of UV Cet stars lie within the range of values predicted from the hypothesis of fast electrons.

2. *Stars of the T Tauri type.* Most of the T Tauri stars possess ultraviolet excesses and, in view of this, they lie on the diagram in a position higher and to the right from the main sequence. In certain cases their difference from the main sequence is as large as 1^m5 to 2^m0. Under these circumstances a comparison of the observed colours of T Tauri stars with the theoretical colour diagram, based on the hypothesis of fast electrons, can prove of definite interest. The most reliable and uniform data on the colours of T Tauri stars are those by Walker (1966) for the very young cluster NGC 2264, and by Smak (1964) for T Tauri stars. On applying those data to our theoretical *(U—B, B—V)* diagram we obtained Figure 3. It can be seen that all the stars lie within the boundaries determined from the hypothesis of fast electrons.

Furthermore, most of the T Tauri stars are located on the diagram in the region where the flare stars rise only during the outburst. In other words, some of the extreme T Tauri stars "live" in the upper part of the diagram permanently, while the occurrence of flare stars in the upper part of the diagram, corresponding to the great activity of the star, is incidental in nature. It would be more correct, therefore, to formulate this situation as follows: T Tauri stars are permanently flaring with a given and practically constant average activity (Gurzadyan 1968). Occasionally this constant degree of activity is increased by short-lived intensification of the activity in the form of ordinary flares (Haro 1962). In such cases the star shifts to an even higher position on the diagram. The nature of both types of activity (permanent and flaring) in T Tauri stars is identical.

All of the T Tauri stars, given in Figure 3, are scattered throughout the interval of activity $\tau \leq 0.1$. At the same time a considerable density of stars is noticeable in the lower part of the diagram. Apparently soon after its birth every star of the T Tauri type appears in the upper part of the diagram, corresponding to a very high ultraviolet activity of a permanent nature. An example given in Figure 3 is NX Mon, a well-known variable star in NGC 2264 (Walker 1965;

Haro and Herbig 1955); at times it has had $U-B = -1^m35$ and $B-V = +0^m57$ (Johnson and Iriarte 1968).

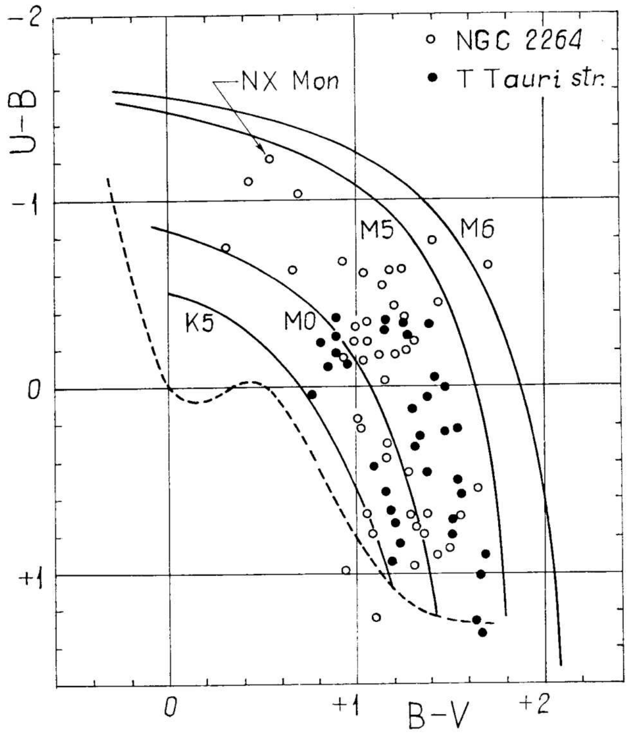

Fig. 3.—*T Tauri stars in NGC 2264 (open circles) and elsewhere (filled circles).*

In this way, an evolutionary interpretation of the peculiar distribution of T Tauri stars on the $(U-B, B-V)$ diagram seems reasonable, although in general this idea is not new. The initial state of the star is the position of an object of the NX Mon type. Later the star descends along the diagram to an intermediate position where "ordinary" T Tauri stars are found. Finally, as the star moves to the region of the main sequence it loses its property of permanent flaring, retaining that of incidental flaring, i. e. it turns into a typical flare star. This model results in the following evolutionary sequence that had already been established by Haro (1962):

Star of the NX Mon type → Ordinary T Tauri star → Flare UV Cet stars

The distribution of the T Tauri stars on the colour diagram does not show signs of clustering or discontinuity. It can be deduced that the evolution of NX Mon → T Tauri → UV Cet proceeds continuously with no appreciable jumps or halts. But the rate of change slows down as the star falls on the diagram; the lifetime of the star in the NX Mon state is the shortest and is of the order of $2-3 \times 10^4$ years.

3. Flare stars in Orion. According to Haro (1969) the number of flare stars in Orion is 254. For 75 of them Andrews (1970) has established photographically their colour indices $U-B$ and $B-V$ for normal stages, i. e. when there is no flare. In Figure 4 we present the data plotted on the colour diagram. An analysis of the diagram leads us to the following conclusions:

i) The distribution of flare stars on the colour diagram does not differ in nature from that of Figure 3 for T Tauri stars of young stellar clusters. This indicates that the nature of permanent non-thermal and non-stable phenomenon in both cases is the same (i. e. in flare stars as well as in T Tauri stars).

ii) It is significant to note that there is a lack of flare stars in that part of the diagram (Fig. 4) which corresponds to the spectral class M5-M6. Judging from this diagram, the flare stars in Orion should belong to a spectral class not later than M2-M3. This conclusion is quite in agreement with the inference by Haro and Chavira (1969) drawn from spectral characteristics, according to which flare stars later than M2-M3 types are lacking in Orion. On the other hand, we have arrived to the same conclusion comparing the *UBV* data with the theoretical colour-colour diagram, based on the hypothesis of fast electrons.

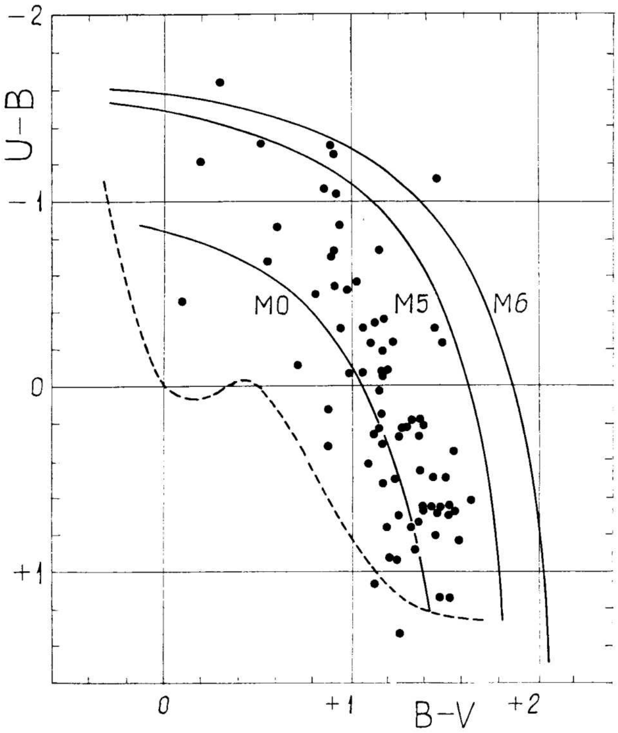

Fig. 4.—*Flare stars in Orion aggregate on the theoretical colour-colour diagram.*

iii) It should be pointed out that the above-mentioned peculiarity of flare stars in Orion, namely, the lack of objects later than M2-M3, established by Blanco (1963) and Haro, is quite reliable. It is relatively simple to recognize the M5-M6 type stars on the objective prism spectrograms (this is due to the characteristic infrared bands of TiO). On the other hand, there are at least 6-7 stars lying within the region M5-M6 in the upper part of Figure 4 (Haro 18, 39, 51, 69, 78, etc.). However, the upper part of the diagram corresponds also to the ultraviolet activity of any star, whether it is of the T Tauri type with H_α emission or simply a flare star. We have no data that these stars were in a state of flare at the time of the measurement; rather the contrary. If this is the case, those stars do not differ at all from NX Mon type stars (permanently flaring stars), as far as their ultraviolet activity is concerned. Further, the continuum coming from powerful permanent non-thermal emission can distort the observed structure of the spectrum of the star (mainly in the ultraviolet). In such situation differences between spectral class and effective temperature of a star are not excluded.

iv) Although a star which lies regularly in the upper part of the diagram (Figure 4) and for which $U-B \sim -1^m3$ to -1^m6 may flare, the amplitude of the flare-up would be considerably smaller than the flare-up of a star which is in the lower part of the diagram. Thus, for instance, a star with an effective temperature corresponding to an M5 main sequence star (with normal colour indices) may theoretically flare up with a U amplitude of up to $9\text{-}10^m$ (Gurzadyan 1968); whereas the flare amplitude for permanently flaring stars (those with abnormal colour indices) cannot exceed $2\text{-}3^m$. Incidentally, the hypothesis of fast electrons enables us to find the correct theoretical ratio between the colour indices and the flare amplitude and thereby to predict the limiting amplitude in a given permanent activity stage of the star, but this subject deserves separate consideration.

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APPENDIX A

The dependence of the function $E_3(\tau)$, $E_4(\tau)$ and $F_1(\tau)$ on the flare intensity, τ, has been tabulated from equations (3) to (6) and is presented in the following Table for a wide range of values.

τ	$E_3(\tau)$	$E_4(\tau)$	$F_1(\tau)$
0	0.5000	1.0000	0
0.0001	0.4949	0.9988	0.00045
0.001	0.4941	0.9975	0.00047
0.002	0.4932	0.9960	0.00094
0.004	0.4914	0.9931	0.00188
0.006	0.4896	0.9901	0.0028
0.008	0.4879	0.9872	0.0037
0.01	0.4861	0.9843	0.0046
0.02	0.4774	0.9698	0.0091
0.04	0.4607	0.9417	0.0169
0.06	0.4448	0.9145	0.0242
0.08	0.4297	0.8883	0.0298
0.10	0.4152	0.8629	0.0369
0.2	0.3516	0.7483	0.0602
0.4	0.2573	0.5674	0.0827
0.6	0.1915	0.4339	0.0872
0.8	0.1443	0.3339	0.0842
1.0	0.1097	0.2582	0.0769

APPENDIX B

The wavelength dependence of the correction function C_λ (μ, τ, T) as defined in equation (1) has been prepared from equation (2) for different spectral types and flare intensities.

$$C_\lambda\ (\mu, \tau, T)$$
$$(\mu^2 = 10)$$

λ	$T = 2500°$ (M6)					$T = 2800°$ (M5)				
	τ					τ				
Å	*1*	*0.1*	*0.01*	*0.001*	*0.0001*	*1*	*0.1*	*0.01*	*0.001*	*0.0001*
2000	2.2×10^8	1.1×10^8	1.3×10^7	1.4×10^6	1.4×10^5	1.4×10^7	6.7×10^6	8.5×10^5	8.6×10^4	8.6×10^3
2500	1.3×10^6	7.5×10^5	6.2×10^5	7.8×10^4	8.0×10^3	1.4×10^5	7.0×10^4	8.7×10^3	890	90.5
3000	4.3×10^4	2.1×10^4	2.6×10^3	267	27,6	7061	3392	426	44.4	5.35
4000	643	309	39.7	4.995	1.39	169	82.0	11.2	2.04	1.10
5000	53.9	26.6	4.22	1.33	1.03	19.1	9.90	2.12	1.12	1.01
6000	10.8	5.94	1.62	1.06	1.00	4.75	3.02	1.25	1.02	1.00
7000	3.64	2.49	1.19	1.02	1.00	1.90	1.65	1.08	1.01	0.999
8000	1.72	1.57	1.07	1.01	0.999	1.05	1.24	1.03	1.00	0.999
9000	1.03	1.23	1.03	1.00	0.999	0.71	1.08	1.01	1.00	0.999
10000	0.726	1.09	1.01	1.00	0.999	0.55	1.00	1.00	0.999	0.999
15000	0.370	0.916	0.991	0.998	0.998	0.342	0.903	0.989	0.998	0.998
20000	0.316	0.890	0.987	0.997	0.998	0.305	0.885	0.987	0.997	0.998
30000	0.289	0.878	0.986	0.997	0.998	0.286	0.876	0.985	0.997	0.998

$C_\lambda\ (\mu,\ \tau,\ T)$
$(\mu^2 = 10)$

λ	T = 3600° (M0) τ					T = 4200° (K5) τ				
Å	*1*	*0.1*	*0.01*	*0.001*	*0.0001*	*1*	*0.1*	*0.01*	*0.001*	*0.0001*
2000						7100	3400	426	44.4	5.35
2500	2593	1246	157	16.9	2.60	354	171	22.3	3.18	1.22
3000	255	123	16.4	2.57	1.16	49.9	24.7	3.98	1.30	1.03
4000	15.0	7.96	1.87	1.09	1.01	4.75	3.02	1.25	1.02	1.00
5000	3.06	2.21	1.15	1.01	1.00	1.37	1.40	1.05	1.00	0.999
6000	1.21	1.32	1.04	1.00	0.999	0.71	1.08	1.01	1.00	0.999
7000	0.71	1.08	1.01	1.00	0.999	0.50	0.98	0.998	0.999	0.998
8000	0.700	0.988	1.00	0.999	0.999	0.412	0.937	0.993	0.998	0.998
9000	0.431	0.946	0.994	0.998	0.998	0.367	0.915	0.990	0.998	0.998
10000	0.383	0.923	0.991	0.998	0.998	0.342	0.903	0.989	0.998	0.998
15000	0.308	0.887	0.987	0.997	0.998	0.297	0.882	0.986	0.997	0.998
20000	0.291	0.878	0.986	0.997	0.998	0.286	0.876	0.985	0.997	0.998
30000	0.280	0.873	0.985	0.997	0.998	0.287	0.872	0.985	0.997	0.998