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The infrared fluxes of early type stars

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Abstract. It is well known that the strong winds of the early type stars modify the fluxes in the infrared and radio wavelength regions. This aspect has been used here to explain the infrared fluxes by the method of 'curve of growth'. Further, it has also been used to derive the excess flux at 3.6 μm, 4.8 μm and 12 μm and compared with observations. The effect of introducing a temperature gradient in the wind has also been studied.

Key words : early type stars—IR flux—stellar winds—free-free emission

1. Introduction

Generally all the early type stars are associated with stellar winds whose effect is distinctly noticeable in the line profiles (Morton 1967). The winds are also sources of free-free emission which are optically thick in the long wavelength regions. This aspect was investigated by Panagia and Felli (1975) as well as Wright and Barlow (1975). The latter demonstrated the use of radio flux measurements for the derivation of mass loss. This technique is extensively used for the early type stars (Abbott *et al.* 1980, 1981).

The wind properties modify the infrared flux distribution as well. Barlow and Cohen (1977) interpreted the IR excess of early type stars in terms of an isothermal envelope. The winds are optically thin in these regions where the IR flux originates and the temperature and density distribution are not easily derivable parameters. Cassinelli and Hartmann (1977) studied the effect of the variation of wind parameters and suggested the possibility of a thin corona (about $0.1R_*$) at the base of the wind.

In recent years, after the IRAS mission, many studies are oriented towards the understanding of the wind properties. Variations of wind parameters like temperature gradient in the wind, different velocity laws etc., are used by different investigators (Leitherer *et al.* 1982, Lamers *et al.* 1984a, Bertout *et al.* 1982). One of them by Lamers and Waters (1984a) who developed the 'curve of growth' method to model the IR region fluxes is of importance in the present context.

The extensive coverage in literature implies the complexity of the situation. In this Paper, we make an effort to model the IR fluxes by the method of 'curve of growth' of

Lamers and Waters (1984a), where the effects of not only free-free emission, but those of bound-free emission and electron scattering are also included. Section 2 describes the data used for this analysis. Section 3 gives a brief description of the method of curve of growth and its application to the present data. Subsequently we derive the expected excess flux variation allowing for a range of wind parameters. In section 4, the effect of temperature gradient is studied and applied to the case of a Wolf-Rayet star. Section 5 concludes the results.

2. Data

The early type stars are easily observable in the near IR and therefore, there is no dearth of data. Almost all the observers have noticed the departure from the model i.e. the 'excess' in majority of the stars. The only exceptions are Sneden *et al.* (1978) and Whittet and van Breda (1980).

The homogeneous data presented by Leitherer and Wolf (1984) is free of the differences in the interstellar reddening corrections and has been used in this Paper. Only 12 stars from their sample have been detected by IRAS and even for these only the flux at 12 μm is reliable. The fluxes at 25, 60 and 100 μm are either uncertain or limiting values. Necessary colour corrections for the IRAS fluxes are applied as described in the explanatory supplement (Beichmann 1985). The $E(B - V)$ provided by Leitherer and Wolf (1984) have been used to derive the interstellar reddening corrections to the observed magnitudes, using the curve no. 15 of van de Hulst.

3. The method of curve of growth

This method has been applied to ε Ori by Lamers and Waters (1984a) to derive the velocity law as well as the mass loss. It makes use of the fundamental definition of the free-free and bound-free absorption coefficient as described below.

The absorption coefficient at any given frequency ν, can be written as,

$$K_\nu = 3.692 \times 10^8 \{1 - \exp(-h\nu/KT) Z^2\{g + b\}T^{-1/2} \nu^{-3} \gamma n_i^2 \qquad \ldots (1)$$

where $\langle Z^2 \rangle$ = mean value of the square of the atomic charge, γ = ratio of number of electrons to number of ions, T = temperature of gas in K, ν = frequency in Hz, $g = g(\nu, T)$ = gaunt factor for free-free emission, $b = b(\nu, T)$ = gaunt factor for bound-free emission.

From the equation of mass conservation at a distance r from the star, we have

$$\dot{M} = 4\pi r^2 v(r)\rho(r) = 4\pi r^2 v(r) n_i(r)\, \mu m_H \qquad \ldots (2)$$

where $\dot{M}$ = mass loss in g/s, $v(r)$ = velocity in cm/s, r = distance in cm, $\rho(r)$ = density in g/cm^3, μm_H = mean atomic weight of the ion in g.

Combining (1) and (2) the absorption coefficient can be re-written as,

$$K_\nu(x) = E_\nu(x) \{R_* w^2(x) x^4\}^{-1} \qquad \ldots (3)$$

where x is the non-dimensional distance in terms of stellar radius R_*, $x = r/R_*$ and $w(x)$ is the non-dimensional velocity in terms of V_∞, $w(x) = v(r)/V_\infty$. $E_\nu(x)$ is the optical depth parameter for free-free and bound-free emission, given by

$$E_\nu(x) = X_* X_\lambda \qquad \ldots (4)$$

with $$X_* = 5.336 \times 10^{31} Z^2 \gamma \dot{M}^2 T^{-3/2} \mu^{-2} V_\infty^{-2} R_*^{-3} \qquad \ldots (5)$$

and $$X_\lambda = \lambda^2 \{1 - \exp(-h\nu/KT)/(h\nu/KT)\} (g(\nu, T) + b(\nu, T)) \qquad \ldots (6)$$

with $\dot{M}$ = mass loss rate in $M_\odot$/yr, λ = wavelength in cm, V_∞ = terminal velocity in km/s, R_* = stellar radius in $R_\odot$.

The ratio of the total flux F_ν due to the photospheric radiation and the wind to that only due to the photosphere is defined as

$$Z(E_\nu) = Z_1(E_\nu) + Z_2(E_\nu) \{B_\nu(T)/I_\nu^*\} \qquad \ldots (7)$$

with Z_1 representing the photospheric radiation, and Z_2 the wind emission. These are integral functions of the optical depth τ_{max} and are tabulated by Lamers and Waters (1984b). Here,

$$Z_1 = \int \{\exp(-\tau_{max}(q)\} 2q \, dq$$

and $$Z_2 = \int [1 - \exp(-\tau_{max})] 2q \, dq$$

where q is the impact parameter and τ_{max} itself is defined as,

$$\tau_{max} = E_\nu \int w^{-2} x^{-3} (x^2 - q^2)^{-1/2} \, dx \quad \text{for } q < 1$$

$$= E_\nu \int w^{-2} x^{-3} (x^2 - q^2)^{-1/2} \, dx \quad \text{for } q \geq 1.$$

The geometry defined requires $z^2 = x^2 - q^2$ (for details, see Lamers and Waters 1984a). The excess flux ratio at ν is then $(Z_\nu - 1)$.

These are computed at the wavelengths where the observations are available, like J, H, K, L, M from Leitherer and Wolf (1984) and 12 μm from IRAS PSC (1987). This is done by first calculating the X_* and E_ν and using the tables of Lamers and Waters (1984b) to get corresponding values of Z_1 and Z_2. Then equation (7) is used to derive Z.

The velocity law chosen is of the type

$$w(x) = w_0(1 - w_0)(1 - x_0/x)^\beta \quad \text{for } x > x_0. \qquad \ldots (8)$$

Numerical calculations were carried out for various values of β = 0.5 to 4 and w_0 = 0.001 to 0.003.

These values may then be compared with observations by calculating the excess flux ratio as observed. For this purpose the corresponding models of Kurucz (1979) at the appropriate T_{eff} are used. The other parameters viz. $<Z^2>$, γ, $\dot{M}$, μ and g have been taken from Lamers and Waters (1984a) and Leitherer (1991).

The gaunt factor provided by Lamers and Waters (1984b) needs to be corrected as suggested by Leitherer (1991, in the Appendix). In case of ε Ori, which was used for the demonstration of the method by Lamers and Waters (1984a), we revised the calculations using the new g factors. This does not alter their conclusions regarding the wind properties; however, the derived mass loss changes to 3.1×10^{-6} $M_{\odot}$/yr.

Figure 1 shows the theoretical curve of growth and observations of HD 152408. It may be seen that β = 3 to 4 is a proper range for the velocity variation. It may also be seen that velocity laws change in the longer wavelength region as the terminal velocity is approached.

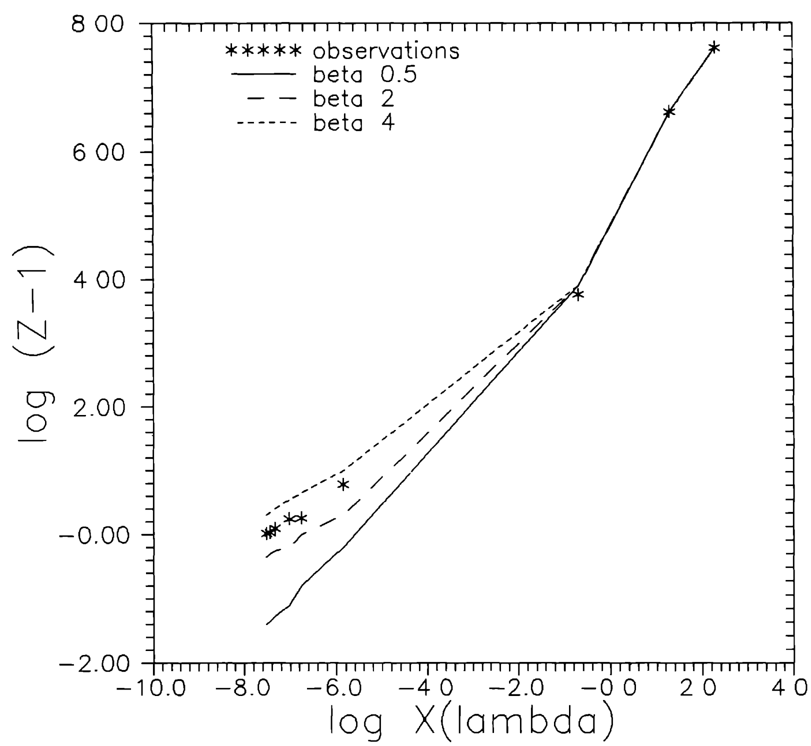

Figure 1. The 'curve of growth' for HD 152408. The abcissa is X_λ, which is a function of the wavelength and wind parameters (see text). The ordinates are the logarithm of the excess flux ratio (Z – 1); the excess with respect to the Kurucz model at the T_{eff}. The value of X_λ near +3 corresponds to the radio region, while that between –6 and –8 approximately refers to the optical and near IR region, where, as is clear, the effect of the wind parameters are quite significant.

Lamers and Waters (1984c) have discussed the effect of a thin corona at the base of the wind. Lamers *et al.* (1984) have applied it to the case of ζ Pup and shows that the existence of such a corona need not be invoked. Therefore, here we have not taken into consideration the possibility of a corona.

Figure 2 gives the comparison of the energy distribution as obtained from the wind emission with observations for HD 152408. The agreement is immediately apparent. It also includes the case of τ Sco. The other stars which have been studied by this method are listed in table 1, along with the various stellar and wind parameters.

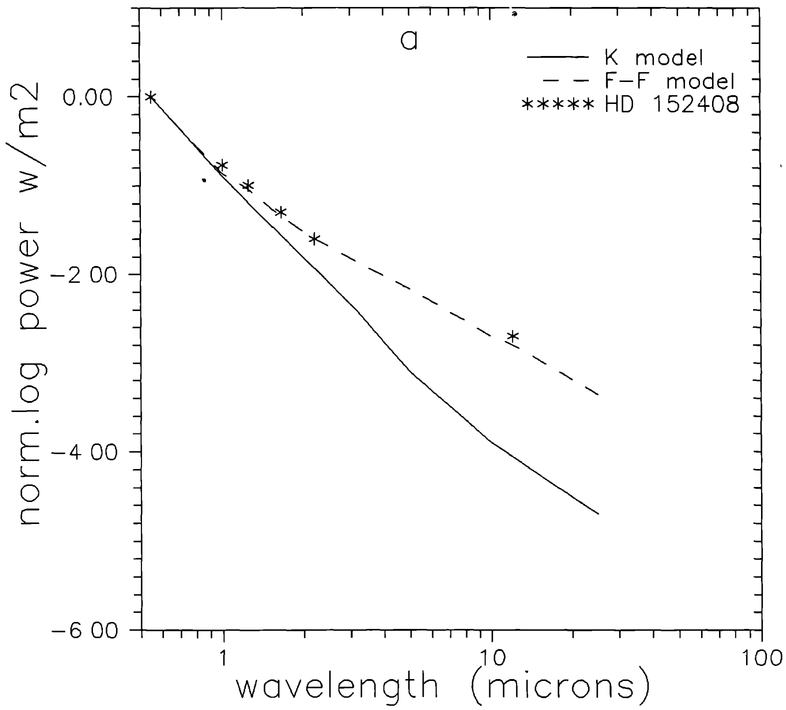

Figure 2a. The energy distribution of HD 152408. The ordinates are normalised (at 5560A) log λF_λ in watts/m^2; the abcissa is wavelength in microns. The solid line represents the Kurucz model while the dashed line is calculated as explained in the text to include the f-f and b-f emission from the wind.

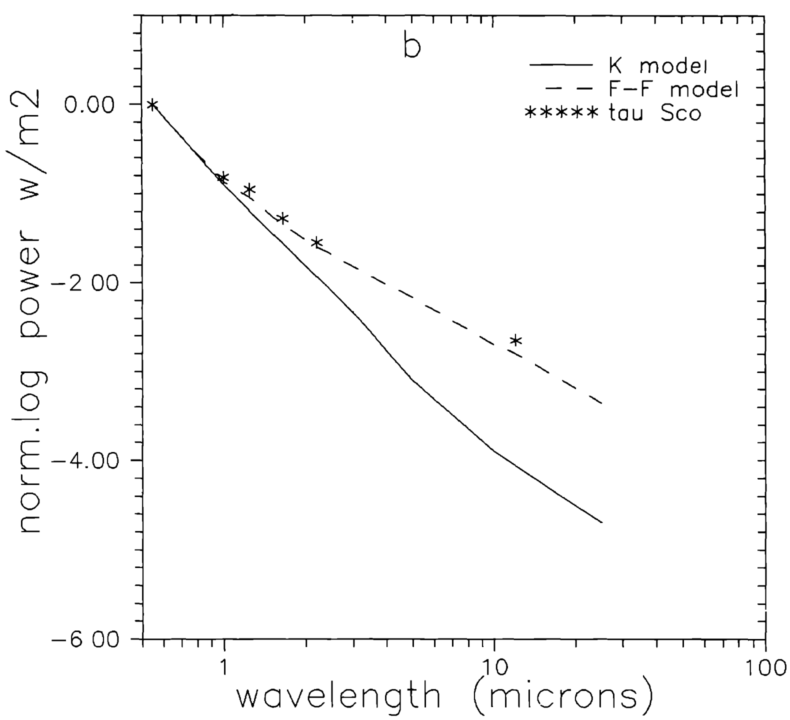

Figure 2b. The energy distribution of τ Sco. Other details are same as in figure 2a.

Table 1. Stellar and wind parameters

HD/name	152408	152236	τ Sco	ε Ori	η CMa	15570	14947
T_{eff}(K)	34200	19000	32000	26400	13000	42500	39000
$R_*(R_\odot)$	30	98	6.7	31.9	56.3	14.5	18.7
T_w(K)	13000	7000	25800	21100	10400	15000	15000*
log $\dot{M}$ ($M_\odot$/yr)	–4.75	–4.83	–7.13	–5.50	–6.42	–5.0*	–5.62
v_∞ (km/s)	955	390	2000	2100	590	2000*	2000*
ΔL (mag)	0.3-0.5	0.05-0.2	0.3-0.45	0.15-0.3	0.05-0.1	0.2-0.3	0.3-0.5
ΔM (mag)	0.2-0.4	0.05-0.15	0.1-0.2	0.05-0.15	0.05-0.1	0.2-0.4	0.2-0.35
Δ[12]	0.15-0.3	0.1-0.2	0.15-0.25	0.15-0.25	0.1-0.2	0.3-0.5	0.2-0.4

*Assumed values.

It is possible to calculate the excess emission as predicted by this model. This has been attempted assuming approximate Gaussian profiles for the filter characteristics for 12 μm as given in Beichmann *et al.* (1985) and for L (3.6 μm and $\Delta\lambda$ = 1.2 μm) and M (4.8 μm and $\Delta\lambda$ = 0.8 μm). The excess flux is measured over the continuum as defined by the Kurucz model and the free-free model and the difference in flux is converted into magnitudes to facilitate the comparison with observations. The resulting values are plotted in figure 3 as a function of the T_{eff}. For a given T_{eff} it is possible to have a range of ΔL and ΔM depending on the choice of the wind parameters, like w_0 and β. Further, the choice of the T_w also is very critical. Depending on whether T_w is 0.4 T_{eff} (Leitherer 1991) or 0.8 T_{eff}, these values change. Table 1 includes the range of excess, which are the extreme values corresponding to the different velocity laws and different T_w and a linear fit through these ranges are indicated in figure 3. It is interesting to compare this with the observations of Leitherer and Wolf (1984), who found a similar trend in L and M bands, i.e., large range for these indices at earlier spectral types. Figure 3a includes the IRAS data for a smaller number of stars and a general trend is noticeable as easily as in other cases although from a limited number of sample data points.

The contribution from various spectral lines in these filter ranges have not been included. This may partly explain the scatter and the observation that some stars have more flux than predicted by these models.

The effect of electron scattering was also calculated by the method described by Lamers & Waters (1984a). The absorption coefficient is given by

$$\sigma = 0.66524 \times 10^{-24} \, (1 - 2h\nu/mec^2)n_e. \qquad \dots (9)$$

However, the results differ only by about 10% by neglecting these effects. Therefore, they have not been included in the final calculation of the ΔL, ΔM and Δ [12 μm].

4. The temperature gradient in the wind

The introduction of a temperature gradient is not very essential for the sample selected here, because a proper choice of the velocity law and wind temperature can explain the observations. This was attempted for the Wolf-Rayet star WR6 (HD 50896). It is known that the photospheres of these WR stars are extended and simple models of Kurucz (1979) are not applicable.

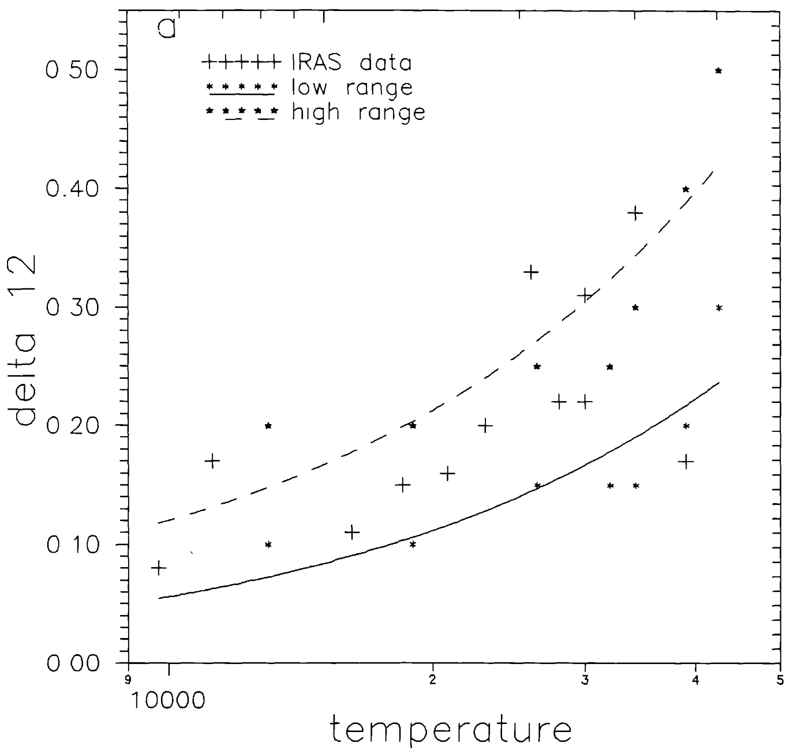

Figure 3(a)

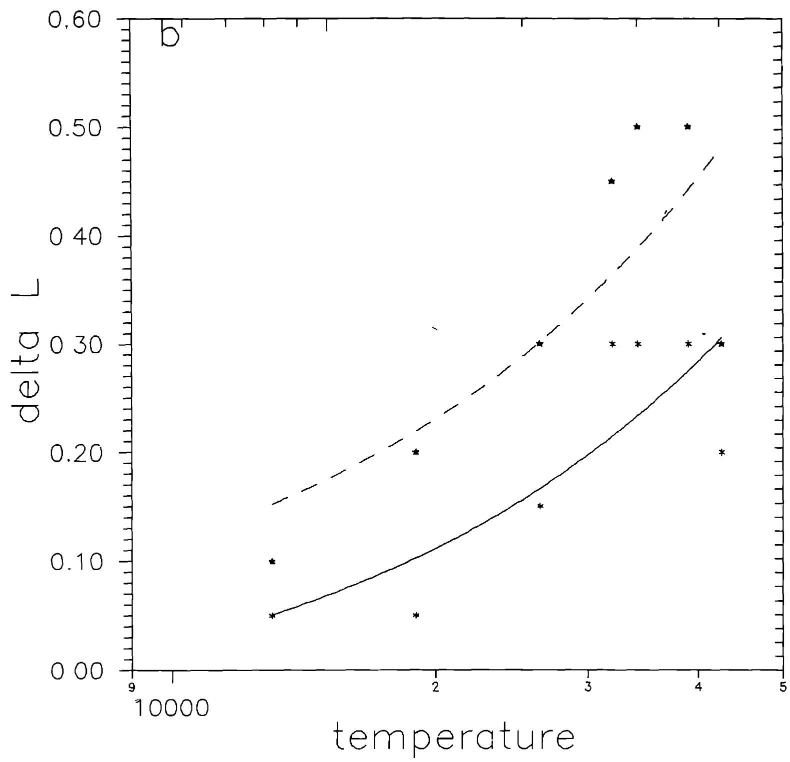

Figure 3(b)

Figure 3(c)

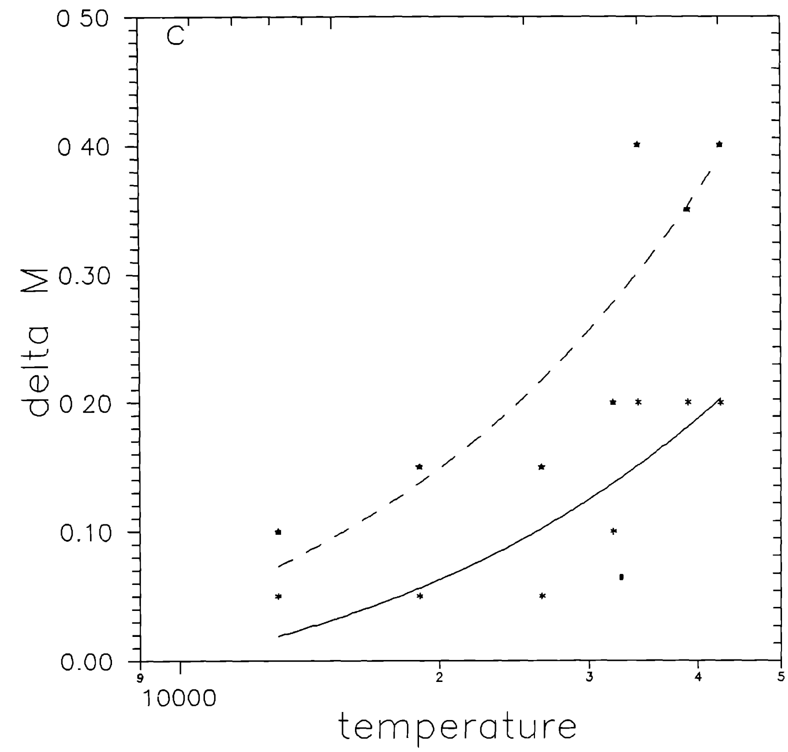

Figure 3. The variation of indices representing the emission due to the wind, measured as the excess flux above the continuum and converted to magnitudes with T_{eff} (x-axis). For the stars of table 1 the ranges in these indices are calculated as explained in the text, by varying the wind parameters. The lines represent a linear fit through these ranges tabulated in table 1. (a) Δ[12 μm] corresponding to 12 μm. Here the observed values are indicated by '+'; the higher and lower range by different symbols. (b) ΔL for the L band, only the ranges are indicated, and (c) ΔM for the M band.

However, as an exercise we proceeded with a Kurucz model for T_{eff} = 40000K and β = 0.5 to 1 (as suggested by Doom 1988).

In case of the well studied WR star, γ^2Vel, the temperature in the wind, responsible for the radio emission, has been derived as 5800K (Hogg 1975). From the photospheric temperature of 26000K, a value for the temperature gradient ($T \propto r^{\alpha}$) can be derived as $\alpha \equiv -0.2$. This value has been used here. The other parameters $<Z^2>$, γ, $\dot{M}$ and μ are from van der Hucht *et al.* (1986).

The effect of electron scattering cannot be neglected here. The total fluxes due to the photosphere and the wind are computed for free-free and bound-free emission as was done in the previous section for the O type stars [let us call them as $F_\nu(E_s = 0)$]. These are now modified taking into account the electron scattering, by making use of the definition of optical depth as described below.

The optical depth due to electron scattering is defined as,

$$\tau_s\ (0.5x_f) = 1.45\ E_s(\pi E_\nu)^{-1/3} \qquad \ldots (10)$$

where the impact parameter x_f defines the effect of electron scattering (Lamers and Waters 1984a) and E_ν is $E_\nu(E_s = 0)$. The optical depth parameter for electron scattering is obtained by combining (9) with (2) as,

$$E_s = 2.887 \times 10^8 (\gamma/\mu) R_*^{-1} \dot{M} v_\infty^{-1}. \quad \ldots (11)$$

(Notice the typographical error in Lamers and Waters 1984a).

The total fluxes, F_ν, thus computed (which include the effects of free-free, bound-free and electron scattering) are now used for comparison with observations.

The curve of growth for the different cases are shown in figure 4 along with the observations taken from the compilation of Gezari *et al.* (1987) and the IRAS PSC (1987). The mismatch in the long wavelength regions ($\log X_\lambda > -6$) is quite obvious. The predicted energy distribution

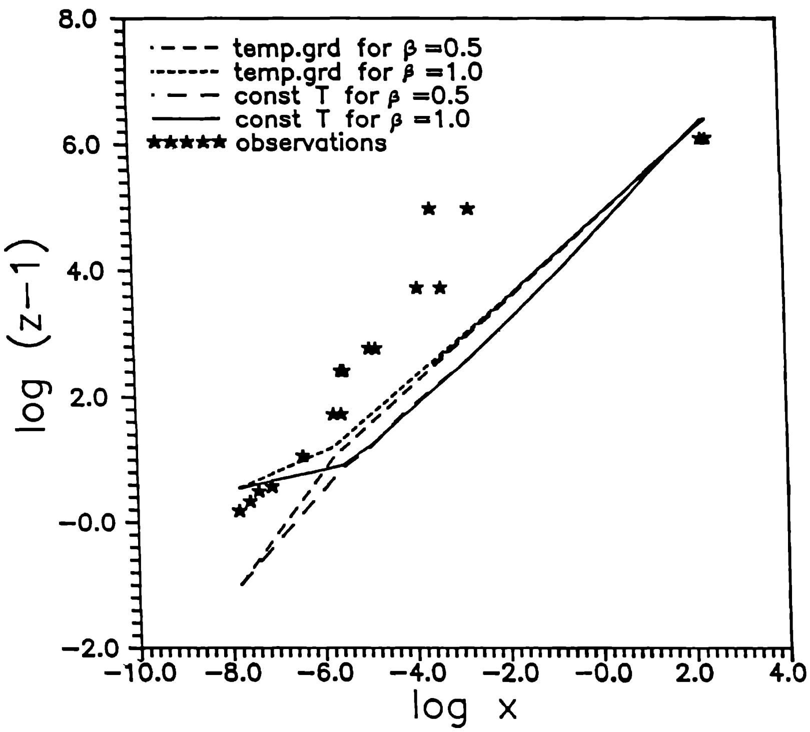

Figure 4. The 'curve of growth' for WR 6, for different values of β and with and without temperature gradient. The other details are same as in figure 1.

is compared in figure 5 along with the observations of another star WR 139 of similar spectral type. It is interesting to see that the near IR observations agree fairly well but not the mid IR fluxes only for the star WR 6. A model for WR 6 by Hillier (1989) taking into consideration the extended atmosphere, can also explain the near IR fluxes. However, the departure from the model flux at λ > 25 μm has attributed to the nebular dust emission (Schmutz 1991).

Thus it appears that the temperature gradient in the wind can be invoked in some exceptional cases to explain the observed IR fluxes.

5. Conclusions

It is possible to explain the IR fluxes of the early type stars based on the models of wind with varying velocity law and temperature. The method of the 'curve of growth' is an effective tool for this purpose. The range of excesses as observed at *L*, *M* and 12 μm wavelength

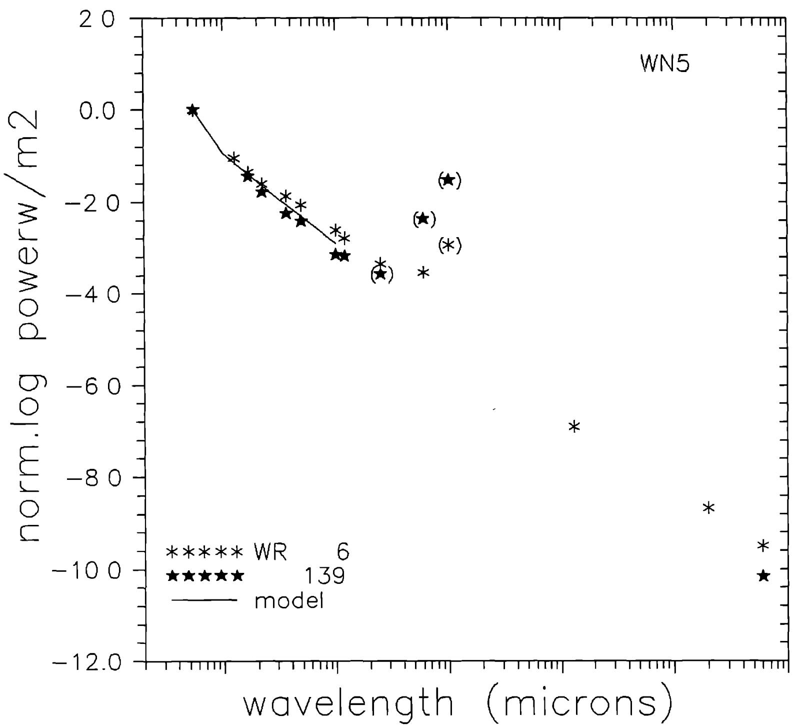

Figure 5. The energy distribution of WR 6 and WR 139, compared with the continuum derived from the wind model. The ordinates are normalised log λF_λ in w/m^2 and the abcissa, the wavelength in microns. The uncertain values from IRAS PSC are enclosed in parenthesis. Both stars are of spectral type WN 5.

bands may be attributed to the varying wind parameters. A temperature gradient in the wind can also explain the excesses in some exceptional cases.

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