INFRARED OBSERVATIONS OF Be STARS

(Review Paper)

Henny J.G.L.M. Lamers
Center for Astrophysics and Space Astronomy
University of Colorado, Boulder
and
SRON Laboratory for Space Research
Utrecht, the Netherlands

I. INTRODUCTION

The first indication that Be stars have an excess near-IR radiation, compared to normal stars of the same spectral type was found by Johnson et al. (1966). Johnson (1967) noticed that in his sample of 85 early type stars all the Be stars and shell stars had an excess in K-L and he concluded that this is due to IR emission from circumstellar shells. Woolf et al. (1970) suggested that the IR excess of Be stars might be due to free-free emission in the ionized circumstellar envelope which also produces the Balmer emission lines, but their observations at 5 and 10 μ could not rule out the possibility that circumstellar dust contributed to the excess. The observations by Allen (1973) of a large number of Be stars up to a wavelength of 3.5 μ could not make the distiction between free-free or dust emission either.

The first conclusive evidence about the nature of the IR excess from Be stars was found by Gehrz et al. (1974) based on the observations of 33 'classical' Be stars at eight wavelengths between 2.3 and 19.5 μ. They concluded that the circumstellar dust emission model is ruled out on the basis of the energy distribution of the IR excess. The typical energy distribution of a Be star in the near-IR contains three parts: a photospheric black-body spectrum at $0.5 \lesssim \lambda \lesssim 1\ \mu$; a region where the slope of the spectrum is less steep than the black-body spectrum, this is generally at $1\ \mu \lesssim \lambda \lesssim \lambda_c$; and a turnover at λ_c so that at $\lambda > \lambda_c$ the slope is again as steep as a black-body spectrum, i.e. $F_\nu \sim \nu^2$. The turnover point occurs at $\lambda \gtrsim 7\mu$. Gehrz et al. showed that this energy distribution can be explained by a simple model of an equatorial shell with a mean density n_s, a temperature T_s and an outer radius R_s. The excess at $1\mu < \lambda < \lambda_c$ is due to the fact that the disc is optically thin for free-free absorption at short wavelengths, and the black-body spectrum at $\lambda > \lambda_c$ is due to the fact that the disc is optically thick at $\lambda > \lambda_c$. The turnover occurs at the wavelength where the optical depth of the disc is unity. The measurement of λ_c and of the excess flux at $\lambda > \lambda_c$ allowed a straightforward determination of n_s and R_s. The temperature T_s was chosen in between 10^4K and the photospheric temperature. This resulted in a mean density of $n_s \simeq 4.10^{11}$ cm^{-3} and mean radius of $R_s \simeq 4\ R_*$ ($\simeq 3\ 10^{12}$ cm) for a typical disc of a Be star. These values agree reasonably well with those derived from the studies of the optical hydrogen recombination lines, which confirms the assumption that the Balmer emission lines and the IR excess are formed in the same region of

https://doi.org/10.1017/S0252921100116288 Published online by Cambridge University Press

the circumstellar material.

Since 1974 many ground-based observations of the near-IR excess of Be stars have been made (e.g. Mendoza, 1982; Feinstein, 1982; Dachs and Wamsteker, 1982; Neto and de Freitas Pacheco, 1982; Ashok et al., 1984; and the poster papers in these proceedings by Kilambi et al., Mendoza, and Persi and Ferrari-Toniolo). The IRAS satellite has observed many Be stars (~ 100) at 12 and 25 μ, a smaller number (~ 25) at 60 μ and one star, δ Cen, at 100 μ (Coté and Waters, 1986; Waters 1986a and 1986b; Waters and Taylor, 1986; Waters et al., 1986).

In Sections II and III I will discuss the IRAS observations of the Be-stars and the correlations between the IR excess and the stellar parameters. Section IV describes the quantitative interpretation of the IR excess and the results in terms of characteristics of the circumstellar material. In Section V I will describe some of the major problems of the IR studies of Be stars and possible future investigations.

I will not discuss the profiles of the near IR emission lines. By far the most information about the structure of the circumstellar material is derived from the Balmer emission lines, which will be reviewed by Dachs. The very few observations of the profiles of the Paschen and Brackett lines in Be stars will be mentioned briefly in Section V. For a review of the spectroscopic observations in the near IR, the reader is referred to the paper by Houziaux and Andrillat (1982) in the previous symposium on Be-stars, and to the posters of Andrillat, Pastori and Persi and Ferrari-Toniolo.

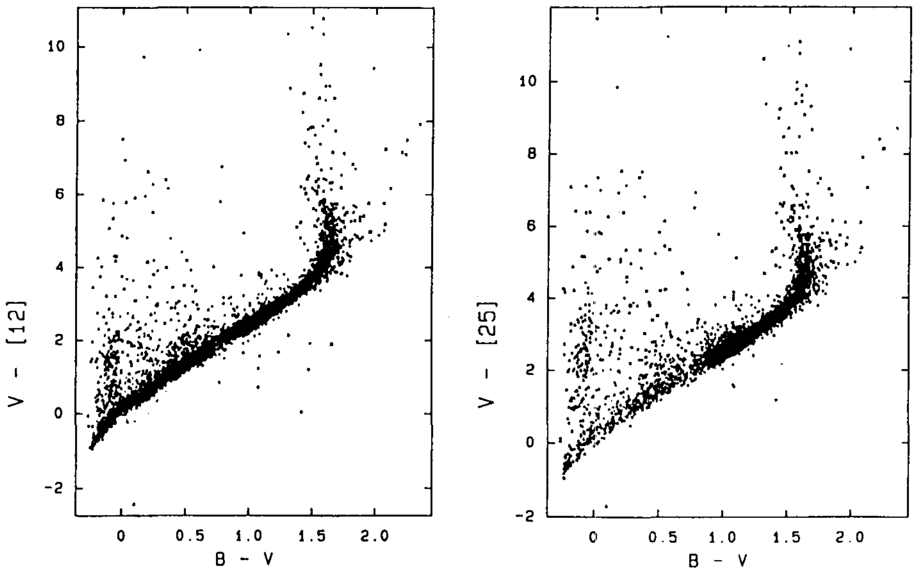
II. IRAS OBSERVATIONS OF Be STARS

The IRAS observations of stars can be expressed in a magnitude scale of [12], [25], [60] and [100]. The zero points of this scale correspond to 3.12 10^{-12}, 4.48 10^{-13}, 4.00 10^{-14} and 4.86 10^{-15} W/m^2 in the IRAS bands at 12, 25, 60 and 100 μ respectively. The stars which are listed in the Bright Star Catalogue and in the IRAS Point Source Catalogue (IRAS Explanatory Supplement, 1985) are plotted in colour diagrams of V-[12] and V-[25] versus B-V in Figure 1 (from Waters et al., 1986). The figure shows a large concentration of stars along a well defined sequence. These are the stars which do not show an IR excess. Waters et al. have used this sequence to define the intrinsic colour $(V-12)_0$ as a function of $(B-V)_0$ and spectral type for normal stars. It turns out that the derived intrinsic V-12 magnitude for early type stars is about 0.1 magnitude larger than predicted for the plane-parallel LTE model atmospheres by Kurucz (1979).

The early type stars with B-V $\lesssim$ 0.3 which are above the relation for normal stars are mostly Be stars with an excess at 12 and 25 μ. Fortunately, the vector of the interstellar reddening is almost parallel to the relation for the normal stars, so uncertainties in the interstellar reddening hardly affect the determination of the IR excesses. (This parallelism is also responsible for the narrow relation defined by the normal stars in Figure 1.)

https://doi.org/10.1017/S0252921100116288 Published online by Cambridge University Press

Fig. 1. The V-12 and V-25 magnitudes of stars listed in the Bright Star Catalogue and observed by IRAS. The narrow band defines the mean relation for normal stars. Most of the stars with B-V < 0.5 and IR excess are Be stars.



The V-[25] versus B-V plot (Fig. 1b) shows a larger fraction of early type stars with IR excess, compared to stars on the 'normal' relation that in Fig. 1a. This is due to the IRAS detection limit: the number of early type stars without excess which are above the detection limit is much smaller at 25 μ than at 12 μ. This trend is even stronger at 60 μ (see Fig. 1 of Waters et al., 1986). Again most of the early type stars with excess are Be stars.

There are 165 Be stars listed in the Bright Star Catalogue (BSC). IRAS detected 101 of these at 12 μ (61%), 69 at 25 μ (42%), and 23 at 60 μ (14%). Only one Be star, δ Cen, was measured at 100 μ, but the 100 μ flux of this star is uncertain due to the complicated background radiation from the interstellar cirrus. In Table 1 I have listed the distribution of the 12 μ excess with spectral type (from Coté and Waters, 1986). The table shows clearly that the upperlimit for the excess at 12 μ decreases towards later spectral types from about $2\overset{m}{.}5$ at early Be to $1\overset{m}{.}5$ at B7-B8 and $0\overset{m}{.}5$ at B9. (The one B9.5 star with a large excess is 51 Oph which has an excess of $3\overset{m}{.}7$. This is the only Be star for which we found clear evidence for IR dust emission: Coté, 1987.) I have also indicated the fraction of the Be stars in the BSC measured by IRAS. There is no clear dependence with spectral type, except for the low percentage at B9. This is most likely due to the small excess of the B9 stars, which implies that most of them will be below the IRAS detection limit.

https://doi.org/10.1017/S0252921100116288 Published online by Cambridge University Press

TABLE I

The 12 μ excess, E_{12}, of Be stars in the Bright Star Catalogue, measured by IRAS.

Spectral Type	Number of stars in BSC	Number of IRAS stars	Ratio	Percentage of stars $E_{12} < 0^m5$	0.5-1	1-1.5	1.5-2	2-2.5	$> 2^m5$
B0-B2.5	64	44	0.69	2	9	12	41	35	2
B3-B4	32	20	0.62	20	10	20	30	20	
B5-B6	26	14	0.54	21	21	21	36		
B7-B8	28	19	0.68	5	84	10			
B9-B9.5	15	4	0.27	75					25

III. CORRELATION OF THE IR EXCESS WITH STELLAR CHARACTERISTICS

In the discussion of the dependence of the IR excess on the stellar characteristics, such as spectral type, v sin i, Hα and polarization, I will often refer to the IRAS measurements, because they provide the largest homogeneous sample of IR measurements of Be stars at present. Moreover, the excesses at 12 μ are larger than those derived from ground-based JHKLM measurements, so that it is easier to detect the presence or absence of correlations.

A. The expected IR excess from optically thin regions

Before discussing the correlation of the IR excess with the stellar characteristics, let us derive a simple estimate for the expected IR excess. Suppose that the IR emitting region is optically thin at 12 μ. Then the free-free radiation can be written as

$$F_\nu \text{ (free-free)} = C_1 . EM . T_e^{-1/2} . \qquad (1)$$

where C_1 is a constant which contains the gauntfactor, the electron to ion ratio and the mean charge of the plasma, EM is the emission measure ($\int n_e^2 dV$) and T_e is the temperature of the emitting region. The photospheric flux can be approximated at long wavelengths by the Rayleigh-Jeans law

$$F_*^\nu = C_2 . R_*^2 . T_* \qquad (2)$$

where T_* is the brightness temperature in the IR. Assuming that the temperature of the emitting region is proportional to the photospheric temperature $T_e \sim T_*$, we expect an excess in magnitudes of

$$\Delta m = 2.5 \log (F_{tot}^\nu / F_*^\nu) = 2.5 \log \left\{ C_3 . \frac{EM . T_*^{-3/2}}{R_*^2} + 1 \right\} \qquad (3)$$

For excesses $\Delta m > 1^m$ we can neglect the term +1 in equ(3) for our simple estimate. So the excess for optically thin emitting regions will depend on the characteristics as

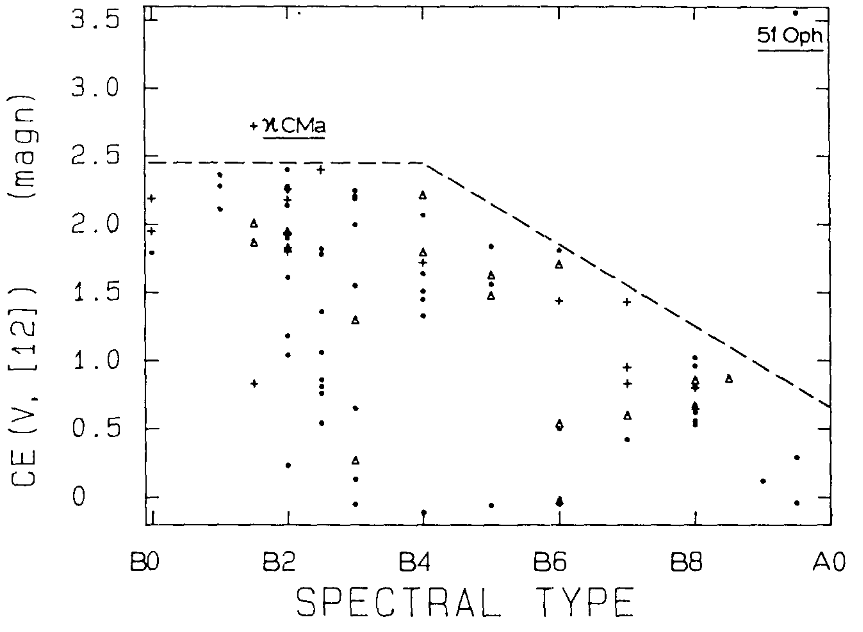
$$\Delta m_{\nu} \simeq \text{Constant} + 2.5 \log EM - 3.75 \log T_{*} - 5 \log R_{*} \qquad (4)$$

we will use this equation to understand some of the observed trends.

B. The correlation between IR excess and spectral type

Figure 2 shows the colour excess (CE) in V-[12] as a function of spectral type for 101 Be stars. The spectral types and the V magnitudes are from the BSC. The data in Fig. 2 show that there is an upperlimit of the excess which varies with spectral type.

Fig. 2. The color excess in V-12 as a function of spectral type. Dots indicate class V; plusses class IV and triangles class III. Notice the existence of an upper limit. The two deviating stars (κ CMa and 51 Oph) are discussed in IIb.



The presence of this limit was already indicated in Table 1. Only two stars are above the limit: 51 Oph (B9.5 Ve), whose IR excess is due to circumstellar dust, and κ CMa (B1.5 IV ne). The colour excess of κ CMa is affected by the visual variability of the star. Dachs et al. (1986) showed that the star brightened by about 0^m.5 in V between 1963 and 1982. The IRAS observations were made in 1983 when the star was 0^m.5 brighter than listed in the BSC. Therefore the true colour excess of κ CMa is likely to be 0^m.5 smaller then shown in Figure 2. The upperlimit in Fig. 2 is not due to a selection effect, since IRAS will preferentially detect stars with large excesses.

https://doi.org/10.1017/S0252921100116288 Published online by Cambridge University Press

The upperlimit is approximately described by:

$$CE\ (V-[12]) \simeq 2^{m}.4 \qquad \text{for B0 to B4} \qquad (5a)$$

$$CE\ (V-[12]) \simeq -0^{m}.35\ S + 3^{m}8 \qquad \text{for B5 to B9} \qquad (5b)$$

where S is the subclass of the spectral type, e.g. S = 4 and 9 for types B4 and B9 respectively. (Coté and Waters, 1986.)

We can compare this behaviour with the expected excess for optically thin circumstellar material. Equation (4) shows that for a constant EM, the excess in magnitudes is expected to increase along the main sequence to cooler stars because both T_{eff} and R_* decrease. So the observed decrease of the excess to later spectral types indicates that the maximum emission measure of the circumstellar material decreases very drastically from B4 to B9 stars.

The rather flat upperlimit for the early-B stars can be due to the fact that the maximum EM does not increase steeply towards earlier types, or that the circumstellar matter becomes optically thick at 12 μ for stars with a large EM. This latter effect will make the dependence of the excess on the EM less steep than in equ. (4).

C. The correlation between IR excess and v sin i

Fig. 3 shows the correlation of CE(V-[12]) as a function of v sin i for the different spectral type intervals.

The figure is basically a scatter diagram with an upperlimit. The stars of types B0 to B3 are found at whole range of v sin i from 40 to 400 km/s with CE(V-[12]) $\lesssim 2^{m}.5$. The stars of types B7 to B9 cover about the same range in v sin i with CE(V-[12]) $\lesssim 1^{m}.0$. There is no correlation of the 12 μ excess with v sin i.

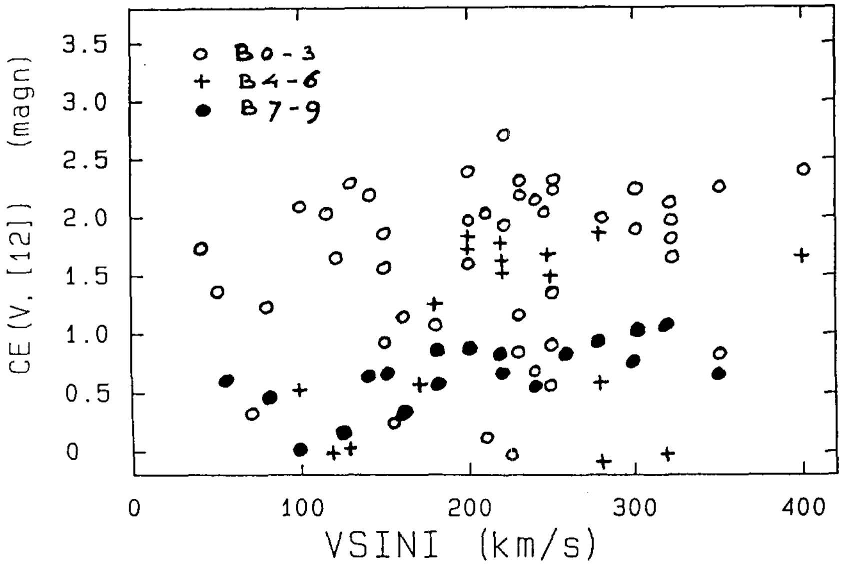
This could be due to a sin i effect. For optically thin circumstellar material the excess does not depend on the inclination angle, even if the matter is concentrated in a flat equatorial disc, so the excess will not depend on sin i, but only on spectral type.

Waters (1986a) has studied the relation between rotation and IR excess from a larger sample of B stars, which includes both Be and normal B stars. He showed that stars can be devided in three regions of v sin i: star with v sin i $< v_1$ tend to have no excess (with a few exceptions); stars with $v_1 <$ v sin i $< v_2$ can have either small or large excess; and stars with v sin i $> v_2$ have large excesses (with a few exceptions). For B0-B4 stars the values of v_1 and v_2 are 100 and 250 km/s respectively. For stars of types B5-B9 the values are v_1 = 200 km/s and $v_2 \gtrsim$ 350 km/s. This shows that rotation does play a role. If the rotation velocity is small, the star does not have much circumstellar matter. If the rotation velocity is large, the star can have an appreciable amount of circumstellar matter, but obviously other factors (not related to the rotation) will determine whether a star will have much circumstellar matter. This agrees with the fact that some stars have been observed to go through phases of Be, B-shell and B normal types, indicating that the

https://doi.org/10.1017/S0252921100116288 Published online by Cambridge University Press

amount of circumstellar material is variable and does not depend on the rotational velocity only.

Fig. 3. The color excess in V-12 as a function of v sin i. The lack of correlation could be due to a sin i effect. Early Be-stars reach larger excesses than late-Be stars.



D. <u>The correlation between IR excess and Hα emission</u>

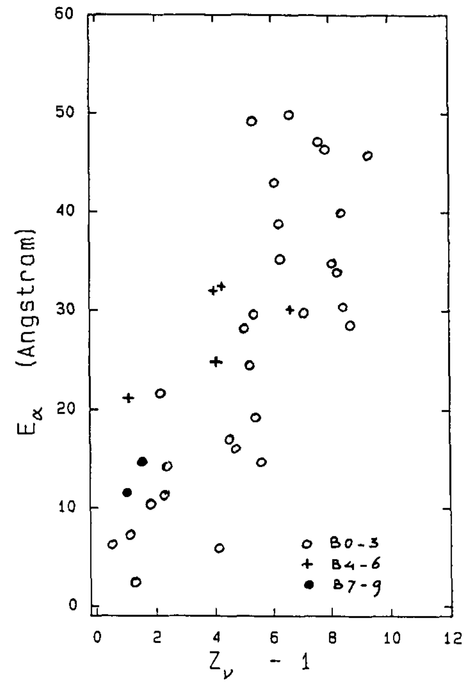
Various authors have pointed out the existance of a 'loose' correlation between the IR excess and the Hα emission in Be-stars (e.g. Feinstein, 1982; Dachs and Wamsteker, 1982; Neto and de Freitas Pacheco, 1982; Ashok et al., 1984 and Coté and Waters, 1986). Figure 4 shows the correlation between the Hα emission, corrected for the presence of underlying photospheric absorption, and the IR excess at 12 μ expressed in terms of the ratio between the free-free flux and the photospheric flux, $Z_\nu - 1 = F_\nu(\text{free-free})/F_*^\nu$, as derived by Coté and Waters. The Hα observations used in this plot are from Dachs et al. (1986) and were obtained in 1983, i.e. in the year of the IRAS observations. The figure shows the existence of a more or less linear relation which goes approximately through the zero point, as expected. The eye estimated mean relation is

$$E_\alpha\ (\text{Å}) \simeq 5.5\ \{F_\nu(\text{free-free})/F_*^\nu\}_{12\mu} \text{ in Å} \qquad (6)$$

This relation clearly demonstrates a common origin of the IR radiation and the Hα radiation from Be-stars.

An even more compelling evidence for a common origin of the Hα emission and the IR excess was found by Dachs and Wamsteker (1982) who showed that for several variable Be stars the increase or decrease of the Hα emission occurs simultaneously with the brightening or fading of the stars in the L-band.

Fig. 4. The relation between the equivalent width of the Hα emission, corrected for the photospheric absorption versus the IR excess at 12 μ. The Hα observations are obtained in the same year as the IRAS fluxes.



The relation between the 12 μ excess and the Hα emission shows a rather large scatter. This may be partly due to the fact that these quantities were not measured simultaneously, but most of it is probably due to optical depth effects in Hα. Neto and de Freitas Pacheco (1982) have studied the relation between the excess at 3.4 μ and the Hα emission in 11 stars and concluded that the typical optical depth in the linecenter of Hα is about 5.10^3. If Hα was optically thin, the line would be about a factor 10^2 stronger than observed (see also Dachs and Wamsteker, 1982; Ashok et al., 1984).

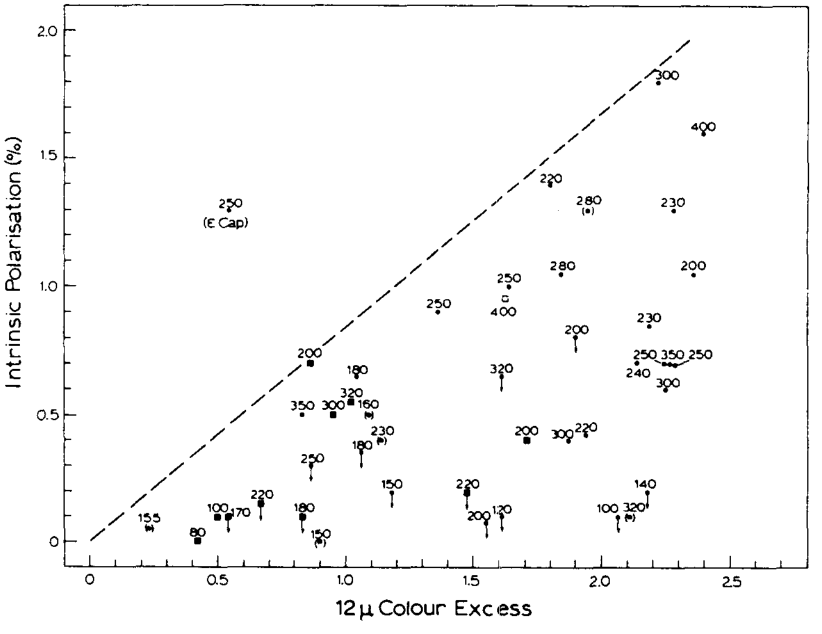
E. The correlation between IR excess and polarization

The intrinsic linear polarization of the radiation of Be stars is due to the scattering of the stellar radiation by free electrons in an equatorial disc (see review by Cassinelli in these proceedings). Since the IR emission is also due to free electrons in the circumstellar envelope one may expect a relation between the degree of polarization and the IR excess. Figure 5 shows the relation between the intrinsic polarization (p in %) of the continuum flux at 4250 Å, measured by McLean and Brown, (1978), and the 12 μ excess derived from IRAS observations by Coté and Waters (1986). Apart from the star ε Cap, which has a highly variable polarization (McLean and Clarke, 1979), there is a well defined almost linear upperlimit in Fig. 5, which is approximately given by

$$p_{max}(\%) \simeq 0.83\ CE(V-[12]) \qquad (7)$$

A similar upperlimit between p and the near IR excess was found by McLean and Brown (1978), who showed that the spread in p, for any value of the IR excess can be due to a random orientation of the inclination angles of the rotation axis if the polarization is due to an equatorial disc, since $p \sim \sin^2 i$. Recent calculations of the polarization produced by discs around Be stars (Cassinelli and Waters, 1987) indicate that the observed upperlimit in Fig. 5 is roughly in agreement with a disc of the type discussed in Section IV with a half opening angle of about 15 degrees. More detailed calculations are required to derive observational constraints for the opening angle or thickness of the discs of Be-stars.

Fig. 5. The relation between the intrinsic polarization and the excess at 12 μ. The existence of an upperlimit indicates that the IR excess is produced in a highly flattened envelope or disc.



IV. QUANTITATIVE INTERPRETATION OF THE IR EXCESS

In this section I will review the results of a quantitative interpretation of the IR excesses. The discussions will be concentrated on the analysis of Be stars which have been observed both in the near-IR

https://doi.org/10.1017/S0252921100116288 Published online by Cambridge University Press

and with IRAS. This group forms a large homogeneous sample with the widest wavelength coverage in the IR. The interpretations in terms of an equatorial disc model will be emphasized because the rapid rotation of the Be stars compared to normal B stars shows that rotation plays some role and the observed polarizations indicate a high degree of flattening of the circumstellar matter. Alternative interpretations will be discussed briefly.

A. Interpretation of the IR excess in terms of a simple disc model

Waters (1986 b) and Waters et al. (1987) have interpreted the near-IR and IRAS observations of Be stars in terms of a simple equatorial disc model and derived information about the density structure of the disc and its EM. The results are qualitatively in agreement with those based on the analyses of the near-IR observations by Gehrz et al. (1974), Neto and de Freitas Pacheco (1982) and Persi and Ferrari Toniolo (1985).

The model consists of an isothermal, rotationally symmetric equatorial disc, which has an opening angle 2θ, a temperature T and a density distribution:

$$\rho(r) = \rho_0 \, (r/R_*)^{-n} \qquad (8)$$

The disc extends to a distance R_d. The free-free and bound-free opacity in the IR, where $h\nu/kT \ll 1$ is:

$$\kappa_\nu = 1.98 \; 10^{-23} \; Z^2 \; (g+b)\lambda^2 \; n_e n_i T^{-3/2} \qquad (9)$$

(Allen, 1973, p. 102), where κ_ν is in cm^{-1} and λ in cm. For a gas in which H and H_e are singly ionized, the mean ionic charge, Z, is about 1.00; and the ion density is $n_i = \gamma n_e$ with $\gamma \simeq 1.00$. The gaunt factors, g and b, for free-free and bound-free absorption respectively are tabulated by Waters and Lamers (1984) and are of order unity.

For such a simple model the excess flux, as seen by an observer in the direction of the poles, can be described analytically (Waters, 1986 b). The spectrum of the IR-excess can be approximated by three linear parts.

i. At short wavelengths, at which the whole disc is optically thin, the ratio between the excess flux, $F_\nu{}^e$ and the stellar flux, $F_\nu{}^*$, is:

$$F_\nu{}^e/F_\nu{}^* \sim \{\lambda^2(g+b)\}^1 \; EM.T^{-3/2} \qquad (10a)$$

ii. At longer wavelengths where the inner part of the disc is opaque but the outer part is optically thin, one finds:

$$F_\nu{}^e/F_\nu{}^* \sim \{\lambda^2(g+b)\}^{2/2n-1} \; C(\rho_o) \; T^{-3/(2n-1)} \qquad (10b)$$

where $C(\rho_o)$ is a constant which depends on ρ_o.

iii. At very long wavelengths where the whole disc is optically thick, the flux emitted by the disc in the direction of the poles is simply $\pi\,(R_d{}^2-R_*{}^2)B_\nu(T)$ and so:

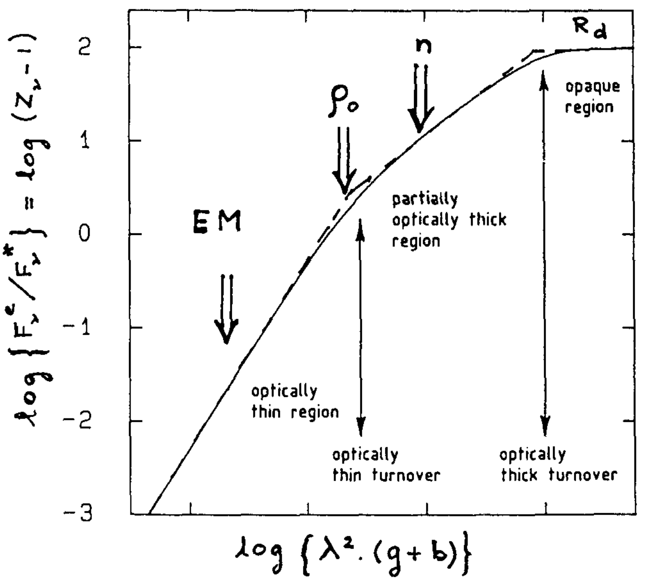
https://doi.org/10.1017/S0252921100116288 Published online by Cambridge University Press

$$F_\nu^e/F_\nu^* = (T/T_*)\{(R_d/R_*)^2-1\} = \text{constant} \qquad (10c)$$

where T* is the brightness temperature of the star in the IR.

These three wavelength regions are schematically shown in Figure 6, which shows the three linear parts, as well as the parameters which can be derived from each part and from the kinks. The optically thin part provides an estimate of the EM.; the slope of the partially optically thick part yields n; the location of the transition between these two parts gives information on ρ_o; and the horizontal part, if observed at long enough wavelengths, gives an estimate of the extent of the disc.

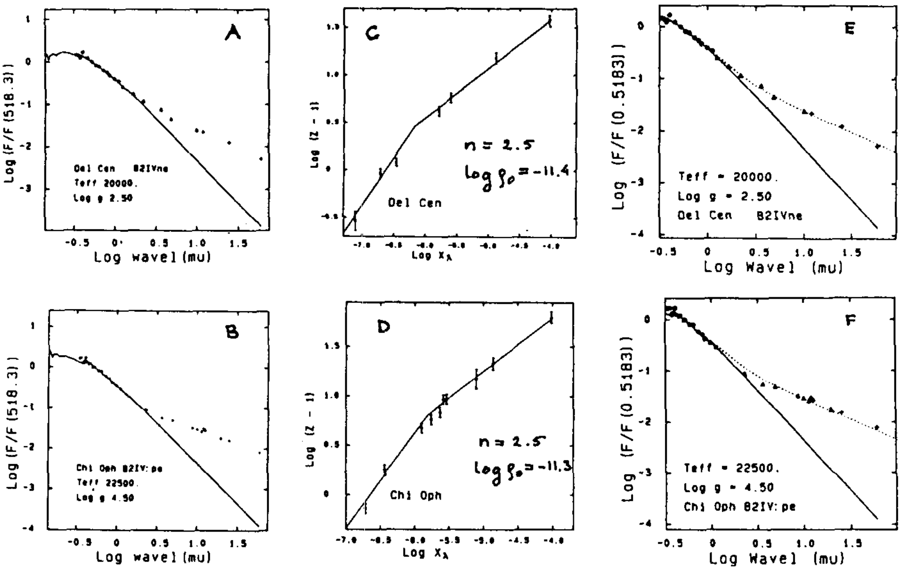
Fig. 6. A schematic picture of the IR excess expected from a disc with the density distribution of equ. (8), as a function of $\lambda^2(g+b)$. The parameters which can be derived are EM, ρ_o, n and R_d.



The observed IR-excess of Be stars indeed shows this predicted wavelength dependence. This is shown in Figure 7 for the two Be stars δ Cen and χ Oph. (from Waters, 1986b). The excess is plotted versus $X_\lambda=\lambda^2(g+b)$ with λ in cm. The excess curves show the two predicted linear parts of equs. (10a) and (10b) and the kink at the transition from the optically thin to the partly optically thick case. The values of the parameters ρ_o and n, which describe the density distribution in the disc, and of the emission measure are indicated in the figure. There is no evidence for a second kink due to the finite size of the disc (equ. 10 c) in the excess curve. This implies a lower limit for the extent of the discs of about 6 R*. Using the parameters ρ_o, n and EM, the predicted shape of the excess spectrum is calculated exactly, and compared with the observations

https://doi.org/10.1017/S0252921100116288 Published online by Cambridge University Press

Fig. 7. The results of the IR analysis of δ Cen (top) and χ Oph (bottom). Figs. A and B: the observed energy distribution as a function of wavelength shows the large excess at $\lambda \gtrsim 2\,\mu$. Figs. C and D: the excess as a function of χ_λ shows two linear parts from which n and ρ_0 can be derived. Figs. E and F: the predicted IR energy distribution compared with the observed one.



to check the accuracy of the fit. This is also shown in Figure 7.

The parameters of the disc models obtained in this way, depend on the validity of the two major simplifications adopted in the analysis: the disc is isothermal and seen pole-on. For an isothermal disc the EM derived from the IR excess is proportional to the adopted value of $T^{1/2}$ (equ. 1). For a non-isothermal disc with a temperature structure $T \sim r^{-m}$ the slope of the excess curve in the partly optically thick region (equ. 10b) changes from 2/2n-1 to (2-m)/(2n-1-3m/2) (Cassinelli and Hartmann, 1979). For m = 2 the uncertainty in n is $\Delta n \simeq 0.5$ if n = 2.5. The effect of different inclination angles on the IR excess has been studied by Bjorkman (1985). She finds that the excess predicted for the disc model is almost independent of sin i, except if $i > 90° - \theta$, i.e. when the line of right from the observer to the stellar center passes through the disc. At such high inclination angles the excess flux decreases very steeply with increasing i.

These considerations give some confidence in the reliability of the characteristics of the discs of Be stars derived from the IR excess by means of the simple model adopted by Waters.

Waters et al. (1987) have analysed the near and far-IR excess of 59 Be stars of spectral types B0 to B9.5 and interpreted the data in terms of the disc model described above, assuming an disc opening angle of $\theta = 15°$ and a disc-temperature of $T = 0.8\ T_{eff}$. The results are summarized in Table 2.

TABLE 2

Characteristics of discs derived from the IR excess

Spectral type	Nr stars	n	log EM (cm^{-3})	logρ_0* (g/cm^3)	log EM max	log ρ_0* max
B0 - B1.5	8	2.9 ± 0.4	60.6 ± 0.5	-11.1 ± 0.5	61.1	-10.4
B2 - B3	21	2.5 ± 0.3	59.4 ± 0.7	-11.4 ± 0.3	60.4	-10.9
B4 - B5	9	2.6 ± 0.5	59.2 ± 0.4	-11.4 ± 0.3	59.9	-10.9
B6 - B7	8	2.4 ± 0.4	58.2 ± 0.6	-11.8 ± 0.4	59.5	-11.2
B8 - B9	7	2.5 ± 0.3	57.7 ± 0.5	-12.0 ± 0.1	58.2	-11.8

* The values of ρ_0 are a factor 0.6 smaller for spherically symmetric models (see IVb)

The EM decreases by about a factor 10^3 from B0 to B9, in agreement with the result shown in Fig. 2. The density gradient in the disc, n, is independent of spectral type for types later than B2, and lies between 2.0 to 3.0. At earlier types, B0 - B1.5, the values of n are on the average slightly higher, ranging from 2.5 to 3.5 with a mean of n = 2.9. This trend is significant and shows that the density in the discs of the early B stars decreases more rapidly with distance than in later types. This might be due to a more rapid acceleration of the disc material. The density ρ_o at the base of the disc decreases by a factor 10 from early to late B stars.

The fact that n is about constant $2 \lesssim n \lesssim 3$ for most of the stars except the early B stars, and independent of the density or emission measure of the disc shows that the discs have a similar structure: the main variation is in the absolute value of the density, but not in its radial dependence.

Although the determination of EM, n and ρ_o for each star is reasonably accurate, the general trends of EM and ρ_o with spectral type in Table 2 may not be meaningful, because they depend on the detection limit of IRAS. The data in Figure 2 show that the IR excess of a Be star can have any value between $\Delta m = 0$ and some maximum. Therefore I have also listed the maximum values of EM and ρ_o for each spectral type.

B. Alternative interpretations of the IR excess

For a spherically symmetric isothermal wind model with a density distribution of equ. (8), the IR excess will show the same general characteristics as for the disc model, i.e. two linear relations of log $(F_\nu{}^e/F_\nu{}^*)$ versus log λ analogous to equs. (10 a) and (10 b) for the optically thin and partly optically thick region. The optically thin part gives information on the EM and the slope of the partly optically

https://doi.org/10.1017/S0252921100116288 Published online by Cambridge University Press

thick part gives the density distribution parameter n. (Wright and Barlow, 1975; Cassinelli and Hartmann, 1979). Therefore, the IR excess of Be stars can also be interpreted in terms of a spherically symmetric envelope. However, such models cannot explain the observed relation between polarization and IR excess shown in Fig. 5.

If the IR excess is interpreted in terms of a spherically symmetric envelope around the star with the density distribution of equ (8) the derived EM will be the same as found for the disc model, but the value of ρ_o will be smaller. The values of ρ_o, listed in Table 2 should be decreased by a factor 0.6 for a spherically symmetric model, but the values of EM and n remain unchanged.

An alternative model for the structure of the circumstellar matter of Be stars was proposed by Doazan and Thomas (1982) and Thomas (1983). It consists of a spherical system which contains from inside outwards: a photosphere, a corona, a high velocity wind, a deceleration region and a high density shell in which the Balmer emission lines and the IR excess are generated. The inner edge of the high density shell is at $r_s \simeq 3$ to 10 R_*. The IR excess of 10 Be stars was interpreted in terms of this model by Lamers and Waters (1987). The characteristics of the excess spectrum are again similar to those of the disc model, but the densities are different. At the inner edge of the shell the densities $\rho(r_s)$ are of the order of $10^{-12.8}$ to $10^{-12.1}$ g/cm^3. This density is a factor 10^4 to 10^6 higher than the density of 10^{-18} to 10^{-16} g/cm^3 of the high velocity wind inside the shell, derived from the UV resonance lines. So, if the high density shell is due to a deceleration of the wind, the deceleration should be a factor 10^{-6} to 10^{-4}, i.e. the wind should be deceleration from a typical value of 2000 km/s to 10^{-3} - 10^{-1} km/s. But this model cannot explain the observed relation between the IR excess and the polarization.

These studies show that the IR excess of Be stars can be explained by a variety of models, but only highly flattened circumstellar envelope models can explain the polarization.

V. PROBLEMS AND FUTURE STUDIES

The existence of a relation between the IR excess and the strength of the emission lines shows that both features are generated in the same region of the circumstellar matter. This is important, because it implies that the information about the density structure derived from the λ-dependence of the IR excess can be combined with the velocity information derived from the line profiles. Up to now, such studies have been attempted for very few stars (e.g. Poeckert and Marlborough, 1978). The extension of the λ-range of IR observations by IRAS and by future mm-telescopes and the availability of the high S/N spectrographs allows such studies for more stars of different types and different IR excesses. The polarimetric observations play a crucial role in these studies and they provide information on the geometry of the circumstellar envelope.

https://doi.org/10.1017/S0252921100116288 Published online by Cambridge University Press

Since Be stars are variable, detailed studies should be based on simultaneous observations of the different spectral characteristics. Unfortunately, very few simultaneous UV, visual, IR, and polarimetric observations were obtained during the year when IRAS was operational.

The relations between the IR excess and other characteristics, in particular the Hα emission and the polarization, gives strong support to disc-type models for Be-stars. The major question of the disc model, which is not solved at present, concerns the origin of the disc: is it due to continuous equatorial outflow with large angular momentum, or is it due to matter expelled by outbursts which revolves around the star in Keplerian orbits thus forming a quasi-stationary disc? The studies of the Hα profiles only do not solve this question (see review by Dachs). The major evidence for a continuously outflowing disc is provided by the study of stars in the B-shell phase, for which the line of sight to the star goes through the disc. Oegerle and Polidan (1984) found that the low excitation UV lines (such as OI, Fe III) of these stars have violet shifted absorption wings up to about -100 km/s, indicating outflow. The observed profiles of the Paschen and Brackett emission lines in γ Cas have also violet wings due to outflow of the disc (Chalabaev and Maillard, 1985; Lowe et al. 1985).

The structure of the discs at distances larger than about 10 R_* is not known. The IRAS observations provide information on the density in the discs up to about 7 R_*. However, a simple extrapolation of the IRAS spectrum up 2 or 6 cm results in radio fluxes which are orders of magnitudes higher than the observed upper limits. So the discs must be limited in their radial extent to $R_d \simeq 10^1$ to 10^2 R_*. Observations with mm-telescopes will allow the determination of the extent of the free emitting region of the disc, by the measurement of the second kink in the IR-excess distributions (Fig. 6).

If the discs are due to outflow, the mass loss through the disc can be derived from the density and velocity distribution. This was done for Be stars observed with IRAS by Waters et al. (1987), as summarized in the poster paper. The mass loss rates turn out to be 10^1 to 10^3 times as large as those derived from UV lines. This shows that the mass flux from the equatorial regions of Be stars are much higher than at higher latitudes. The large difference of a factor 10^1 to 10^3 cannot easily be explained by radiation driven winds of rapidly rotating stars. It is possible that non-radial pulsations are responsible for the enhanced equatorial mass loss (see review by Baade) and that variations in the pulsation modes may induce variations of the amount of mass in the disc which are observed as variations in the strength of the emission lines and of the IR excess.

ACKNOWLEDGEMENT

K. Bjorkman, J. Dachs, H. Henrichs, M. Marlborough, T. Snow and L. Waters are gratefully acknowledged for fruitful discussions and comments on the manuscript. This work was partly supported by NASA grants NSG 5300 and IRAS-JPL 597634 to the University of Colorado, when the author was a summer visitor at the Center for Astrophysics and Space Astronomy.

REFERENCES

Allen, C.W. 1973, Astrophysical Quantities, Athlone Press, London
Allen, D.A. 1973, MNRAS 161, 145
Ashok, N.M., Bhatt, H.C., Kulkarni, P.V., Joshi, S.C. 1984, MNRAS 211, 471
Bjorkman, K. 1986, Private Communications
Cassinelli, J.P., Hartmann, L. 1977, Ap. J. 212, 488
Cassinelli, J.P., Waters, L.B.F.M. 1987 in preparation
Chalabaev, A.A., Maillard, J.P. 1985, Ap. J. 294, 640
Coté, J. 1987 Astr. Ap. (submitted)
Coté, J., Waters, L.B.F.M. 1987 Astr. Ap. (in press)
Dachs, J., Hanuschik, R., Kaiser, D., Ballereau, D., Bouchet, D., Kiehling, R., Kozok, J., Rudolph, R., Schlosser, W. 1986, Astr. Ap. Sup. 63, 87
Dachs, J., Wamsteker, W. 1982, Astr. Ap. 107, 240
Doazan, V., Thomas, R.N. 1982 in Proc. Third European IUE Conference, p. 287
Feinstein, A. 1982, in: Be stars; eds.: M. Jaschek and H.G. Groth, Reidel, Dordrecht, p. 235
Gehrz, R.D., Hackwell, J.A., Jones, T.W. 1974, Ap. J. 191, 675
Houziaux, L., Andrillat, I. 1982 in: Be stars, eds.: M. Jaschek and H.G. Groth, Reidel, Dordrecht, p. 211
IRAS Explanatory Supplement to the Catalogues and Atlasses, 1985, eds.: Beichman, Neugebauer, Habing, Clegg, Chester, JPL D-1855
Johnson, H.L., 1967, Ap. J. Letters 150, L 39
Johnson, H.L., Mitchell, R.I., Iriarte, B., Wisniewski, W.Z. 1966, Comm. Lunar Plan. Lab. 4, 99
Kurucz, R.L. 1979, Ap. J. Suppl. 40, 1
Lamers, H.J.G.L.M., Waters, L.B.F.M. 1987, Astr. Ap. (in press)
Lowe, R.P., Moorhead, J.M., Wehlau, W.H., Barker, P.K., Marlborough, J.M. 1985, Ap. J. 290, 325.
McClean, I.S., Brown, J.D. 1978, Astr. Ap. 69, 291
McClean, I.S., Clarke, D. 1979, MNRAS 186, 245
Mendoza, E.E. 1982 in: Be stars, eds.: M. Jaschek and H.G. Groth, Reidel, Dordrecht, p. 3
Neto, A.G., de Freitas Pacheco, J.A. 1982, MNRAS 198, 659
Oegerle, W.R., Polidan, R.S. 1984, Ap. J. 285, 648
Persi, P., Ferrari-Toniolo, M. 1985 in: Multifrequency behaviour of Galactic accreting sources, ed.: F. Giovanelli, p. 275
Poeckert, R., Marlborough, J.M. 1978, Ap. J. Suppl. 38, 229
Thomas, R.N. 1983 in: Stellar Atmospheric Structure Patterns, NASA SP-471, p. 279
Waters, L.B.F.M. 1986a, Astr. Ap. Letters 159, L1
Waters, L.B.F.M. 1986b, Astr. Ap. 162, 121
Waters, L.B.F.M., Coté, J., Aumann, H.H. 1986, Astr. Ap. (in press)
Waters, L.B.F.M., Coté, J., Lamers, H.J.G.L.M. 1987, Astr. Ap. (in press)
Waters, L.B.F.M., Lamers, H.J.G.L.M. 1984, Astr. Ap. Suppl. 57, 327.
Waters, L.B.F.M., Taylor, R. 1987, Astr. Ap. (submitted)
Woolf, N.J., Stein, W.A., Strittmatter, P.A. 1970, Astr. Ap. 9, 252
Wright, A.E., Barlow, M.J. 1975, MNRAS. 178, 41

DISCUSSION FOLLOWING LAMERS

Hirata:

I also examined the *IRAS* data for all classical Be stars in the BS catalogue, and found the same results as you. I could find no classical Be star with a dust envelope with confidence. What is your result?

Lamers:

Only one classical Be star listed in the Bright Star Catalogue showed the presence of dust: 51 Oph. This star is discussed by Cote (1986).

Kogure:

In the disk model you have adopted, can you determine the vertical extension (the value of θ in your figure) from IR observations? Is there a large variation of vertical extension among Be stars?

Lamers:

Our simple model does not give us any information about the vertical density distribution in the disk. In our model we have adopted a full opening angle of the disk of 30 degrees. Neither the derived emission measure nor the power of the density distribution (n) depends on this angle.

The opening angle of 30 degrees was chosen because the polarization data show that θ is of the order of 10 to 30 degrees.

Underhill:

You spoke of mass loss with flow speeds of the order of or less than 50 kms^{-1}. The distance of this material from the star's surface is less than 100 R_* in your model. Consequently this material will not escape to infinity; it does not have enough momentum. You are discussing material suspended in the vicinity of the star. This material may flow to and fro; it does not escape, thus it is incorrect to speak of mass loss.

Lamers:

Maybe you are right, maybe not. It is true that the velocity in the region of the disk which we see in the IRAS wavelength region (typically $r < 5\ R_*$) is below the escape velocity. However, we do not know how the velocity behaves at larger distances, and it may very well reach higher velocities at larger distances. In fact the evidence of profiles which I presented in the review seems to indicate that the velocity increases outwards at larger distances.

Peters:

The viscosity in the disk might be high enough that the disk material is eventually re-accreted by the star, i.e. "most of what goes up might come back down!"

Lamers:

I agree.

Dachs:

It is a well-known fact that Lyman continuum radiation is not sufficient to produce ionization of circumstellar matter around Be stars. Usually it is suggested that the additional source of ionization you need is absorption of Lyman-alpha followed by absorption of Balmer continuum photons (cf Dachs and Hanuschik 1984).

Doazan:

https://doi.org/10.1017/S0252921100116288 Published online by Cambridge University Press

I would like to make two comments: First, on the absence of a correlation of the IR excess with vsini in Be stars. I have in hand our "bible", which is the Poeckert and Marlborough model, and I note that in the disk model, stars observed equator-on, or nearly equator-on, are less luminous by about 2 mag at 10 μ than stars observed at smaller inclinations. Such an effect is enormous. Therefore, one would expect that under the disk model that you present - which is essentially Marlborough's model, but oversimplified - a clean separation should be observed between B stars exhibiting, or having exhibited shell spectra, i.e. seen equator-on under the disk model, and those who are known to have exhibited only Be spectra. This is clearly not the case since no correlation with vsini is apparent. I would thus conclude that rather than being strongly confined to the equator, the atmosphere of Be stars is largely extended above the equator, i.e. rather spheroidal.

Second, you always obtain accelerating velocity laws. But it is well known from visual observations that v(r) may be accelerating, decelerating, or constant. It would be interesting to inspect visual data obtained at the same epoch for your stars, in order to compare the velocity laws inferred from Balmer lines to your IR results.

Lamers:

With regard to your first question: our calculations show that the excess is almost independent of the inclination angle, except for $i > 90° - \theta$, where θ is the half opening angle of the disk which is about 15o in our model. So, unless the observer is in the plane of the disk, one does not expect a dependence with vsini. This is in agreement with the observations.

Concerning your second question, I do not obtain an accelerating velocity law. What we derive from the IR is the density distribution. If this density distribution is explained in terms of continuous outflow, one must conclude that the acceleration must be increasing outwards in the IR emitting region, which is within $r < 10 R_*$. (The arguments which suggest outflow are given in my review.) It is very well possible that the matter may be decelerated further outward where the cores of the stronger Balmer lines are formed. The IR emission does not provide information about this outward region.