Quantitative IR Spectroscopy of Hot Stars Observed by ISO

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Abstract. In this paper we present quantitative infrared spectroscopic analyses of hot stars based on ISO data. In a pilot study, we first investigate in detail the ISO–SWS spectrum of P Cygni, and the consistency of the results obtained from IR spectroscopy with those from optical studies. Then we present preliminary results from ISO–SWS observations for three more hot stars.

1. Introduction

The dramatic progress of ground-based IR astronomy in this decade has lead to a severe revision of the status of quantitative IR spectroscopy of hot stars, which was clearly lagging behind. Triggered by the detection of the He I cluster at the Galactic centre by Krabbe et al. (1991), recent systematic observational studies in the J, H, and K bands (e.g., Morris et al. 1996; Hanson et al. 1996; Figer et al. 1997; Fullerton & Najarro 1998) have supplied the input for quantitative spectroscopy of early-type stars. The relatively narrow IR window accessible from Earth has been considerably enlarged since the launch of the Infrared Space

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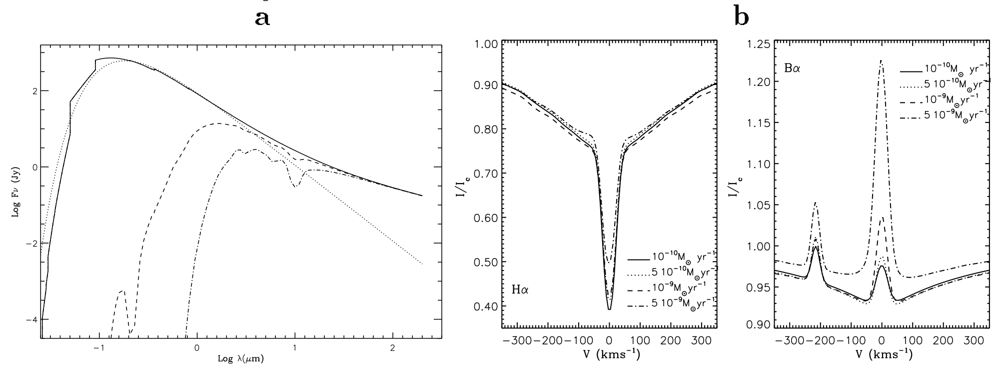

Figure 1. (a) Continuum-flux energy distribution (solid line) of a $T_{\rm eff}$=28kK model with a dense stellar wind, compared with the black-body distribution; note the IR excess. Also shown are the effects of the interstellar reddening for two A_V values: A_V=5 (dashed) and A_V=25 (dashed-dotted); the latter is characteristic of the Galactic centre. (b) Brα and Hα profiles as tracers of a thin stellar wind for a β-Cephei star. The Brα profile is more sensitive (see text).

Observatory (ISO) which is providing, indeed, new light for our understanding of the stellar winds of early-type stars. The SWS (2.38–45.2μm) instrument on board ISO not only opens a new spectral window for quantitative spectroscopy, but also imposes severe new constraints, as we must now be able to reproduce stellar spectra over a very wide spectral range. Once we achieve this, we may then confidently perform infrared quantitative spectroscopy to derive properties of objects in highly obscured regions for which only IR spectra are observable.

We present here, therefore, first results on quantitative infrared spectroscopy of a sample of hot stars observed with SWS. In a pilot study, we will first investigate in detail the stellar properties of the Luminous Blue Variable P Cygni using ISO data, and check for consistency with those obtained by modelling the optical and near-IR H and He I lines. Once we gain some insight into the processes controlling the formation of the IR line profiles, we may confidently proceed to analyse other objects. Preliminary results are presented here for HDE 316285 (P-Cyg-type star), HD 152408 (O8 Iafpe), and λ Cep (O6 I(n)fpe).

2. IR Continuum and Lines as Diagnostic Tools

From the observational point of view, the IR represents an alternative spectral window for those objects which suffer from high interstellar extinction (e.g., the Galactic centre). The observational relevance of the latter is shown in Fig. 1a, where we see how the peak of the continuum energy distribution of an object with $T_{\rm eff} \simeq 30$ kK is shifted to the IR region even for $A_V \geq 5$.

From the theoretical point of view, both the IR *continuum* and *lines* of hot stars are powerful diagnostics for the investigation of the stellar winds surrounding these objects.

- An *IR continuum flux excess* is shown by all early-type stars undergoing moderate mass-loss, which is attributed to the bound-free and free-free emission processes in the stellar wind (e.g., Wright & Barlow 1975, Panagia

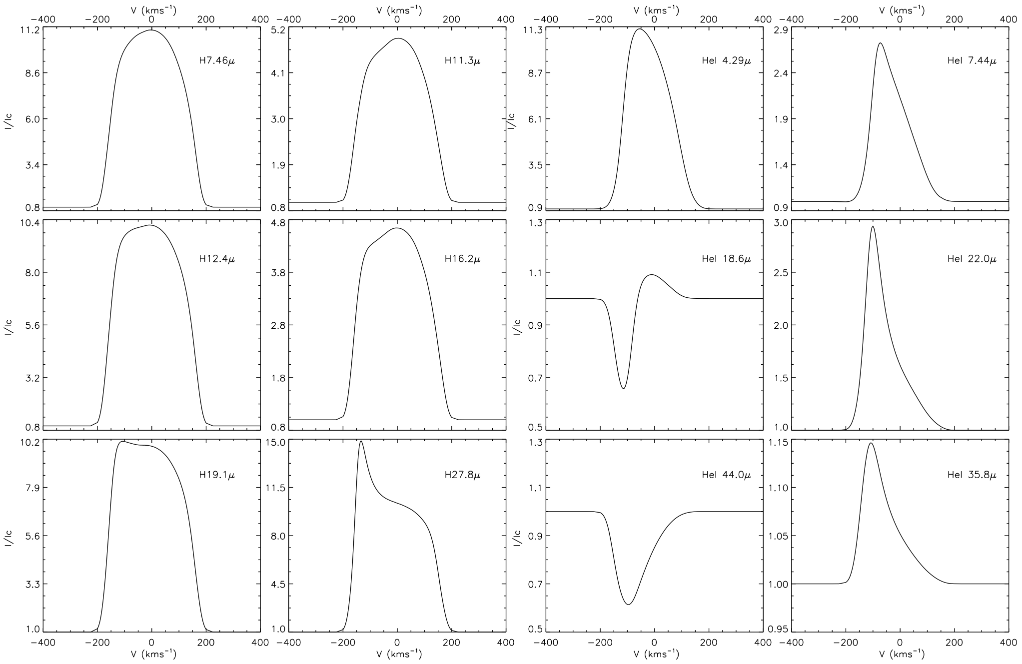

Figure 2. Zoology of H and He I IR-profiles for an extreme B1-supergiant model. The shapes of the profiles are controlled by the effects of continuum opacity and the ratio of the line to continuum opacity.

& Felli 1975). This is also shown in Fig. 1a, where we clearly see how the IR continuum energy distribution takes off from the blackbody distribution. The behavior of the IR excess yields important information to constrain the structure of the stellar wind.

- The *IR line profiles* are even better diagnostic tools. As $h\nu/kT > 1$ in the IR, non-LTE effects in the line profiles are magnified (Mihalas 1978), and even in the case of very *thin* winds, the IR spectral lines become ideal tracers of the presence of the stellar wind. This is illustrated in Fig. 1b, where we see how, for a typical β-Cephei star ($T_{\rm eff}$ = 18kK, $\log g = 3.8$, $R_* = 8R_\odot$), the Brα line is more sensitive to changes in $\dot{M}$ than is Hα. In the case of *dense* winds, both the lines and the continuum are formed in the wind and the behavior of continuum opacity with wavelength gives rise to a *zoology* of spectral lines. This is shown in Fig. 2, where we see how the shapes of the hydrogen and helium profiles are affected as a result of the combination of the line and continuum opacities for an extreme B1 supergiant. The different positions of the profile maxima/minima shown in Fig. 2 demonstrate the importance of the IR line profiles in constraining the wind velocity structure.

3. Observations and Model for P Cygni

ISO–SWS observations and data reduction for P Cygni and other LBVs have been described by Lamers, Morris, et al. (1996). P Cygni's ISO–SWS spec-

Table 1. Derived stellar parameters for P Cygni from optical and infrared observations; β is the steepness parameter of the velocity field.

Model	R_* ($R_\odot$)	L_* ($L_\odot$)	$T_{\rm eff}$ (10^4K)	$n_{\rm He}/n_{\rm H}$	$n_{\rm N}/n_{\rm H}$	$\dot{M}$ ($M_\odot\,{\rm yr}^{-1}$)	v_∞ (km s^{-1})	β
Optical	76	7.0×10^5	1.92	0.29	5.8	3.2×10^{-5}	185	4.5
ISO–SWS	76	5.6×10^5	1.81	0.30	6.0	3.0×10^{-5}	185	2.5

trum (2.38–45.2μm) is dominated by H and He I emission lines and some strong forbidden emission lines of [Fe II], [Fe III], [Ni II], [Ne II], [Ne III], and [Si II]. In addition, we have used the averaged high-resolution (R = 12 000) optical and near-IR spectra (4060–8900Å) from the long-term spectroscopic monitoring of P Cygni carried out by Stahl et al. (1993).

For the spectroscopic analysis we proceed as described by Najarro et al. (1994) and use the iterative, non-LTE method presented by Hillier (1987, 1990) to solve the radiative-transfer equation for the expanding atmospheres of early-type stars in spherical geometry, subject to the constraints of statistical and radiative equilibrium. Steady state is assumed, and the density structure is set by the mass-loss rate and the velocity field via the equation of continuity. The velocity law (Hillier 1989) is characterized by an isothermal effective scale height in the inner atmosphere, $h_{\rm eff}$, and becomes a β law in the wind (e.g., Lamers, Najarro, et al. 1996). The atmosphere is considered to consist of hydrogen, helium, and nitrogen (N II–N III). The model atoms consisted of 15 H, 51 He I ($n \leq 11$), 5 He II, 43 N II and 11 N III levels. The model is then prescribed by the stellar radius, R_*, the stellar luminosity, L_*, the mass-loss rate, $\dot{M}$, the helium and nitrogen abundances, $n_{\rm He}/n_{\rm H}$ and $n_{\rm N}/n_{\rm H}$, and the velocity field, $v(r)$.

We started the analysis with the stellar parameters derived by Najarro (1995), based on a spectroscopic investigation of data from Stahl et al. (1993), from which we obtained a value for the terminal velocity (v_∞=185 km s^{-1}), while the stellar radius was assumed to be R_*=76$R_\odot$ (Lamers et al. 1983). We then relaxed all other stellar parameters and proceeded to model the IR spectra of P Cygni in detail. The main observational constraints were set by the H and He I profiles measured with ISO, but consistency with the optical spectra was also required.

Table 1 shows the model parameters which best reproduce the ISO–SWS lines, together with those obtained by Najarro et al. (1997) from the optical spectroscopic investigation. Notice that the stellar parameters obtained from both analyses agree fairly well. The main difference between the two models is the velocity field in the supersonic part of the wind. To match high Paschen-series lines in the optical we require a steep velocity field close to the photosphere, which switches to a flatter velocity law with β = 4.5 around v_0=80 km s^{-1}(see Fig. 3). However, this velocity field results in much larger equivalent widths for the IR lines in the 2–7μm region than observed, as shown in Fig. 3.

In this spectral range the line-formation regions of the main H and He I lines are located at $v(r) > 0.5v_\infty$, i.e., well beyond the transition zone between photosphere and wind, whereas the continuum is formed around v_0. Hence, if

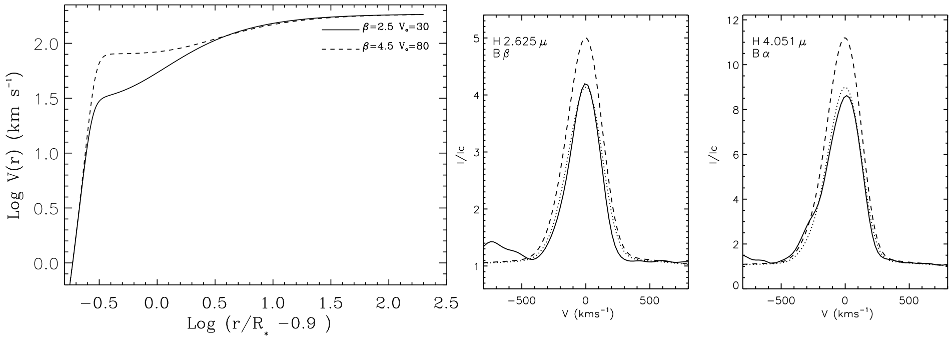

Figure 3. Influence of the velocity field on the IR profiles. Left: velocity field derived from the ISO (solid) and optical (dashed) investigations. Right: the higher transition velocity for the optical models (dashed) produces too-strong emission components in the (2–7μm) range when compared with the observations (solid), while the lower transition velocity of the ISO (dotted) is able to reproduce the observations quite well.

the velocity field is varied in the transition zone, the resulting changes in the equivalent widths will be primarily controlled by the variation of the continuum flux. Therefore, to reduce the computed equivalent widths in the 2–7μm region, a lower value of v_0 (and hence a higher density and continuum flux) is required.

This is achieved in our ISO–SWS model where the transition between the steep photospheric velocity field and the wind regime occurs at about 30 km s^{-1} and the wind velocity law is steeper ($\beta = 2.5$) than that derived from the optical spectrum. Due to the differences in the velocity and density structure of we derive a slightly lower effective temperature ($\Delta T_{\rm eff} = 1000$ K) compared to the model based on the IR observations. Figure 4 shows the excellent agreement of our calculations with the observations. Our model reproduces not only the profiles of the H and He I lines over the whole 2.5–28μm range, but also the optical lines. The model also accounts for the broad electron-scattering wings of the strongest lines. The only discrepancies between our model and the observations are found for the He I 3^3S–3^3P line at 4.29μm which is overestimated, and the absorption components of the high Paschen-series members, which are slightly underestimated. This is due to the lack of metal-line blanketing in our models (for further discussion see Najarro 1995; Lamers, Najarro, et al. 1996).

Good agreement is also found between our model and published photometric observations ranging from the UV to radio (Najarro 1995; Lamers, Najarro, et al. 1996). We derive an extinction of $E(B-V) = 0.51$ which results in a distance of 1.71 kpc. This is within the uncertainty of the cluster distance of 1.8 kpc (Lamers et al. 1983).

4. Preliminary Results for Other Early-Type Stars

New ISO–SWS observations have been obtained recently for three other objects, namely HDE 316285 (B1 Ia$^+$), HD 152408 (O8: Iafpe), and HD 210839. For

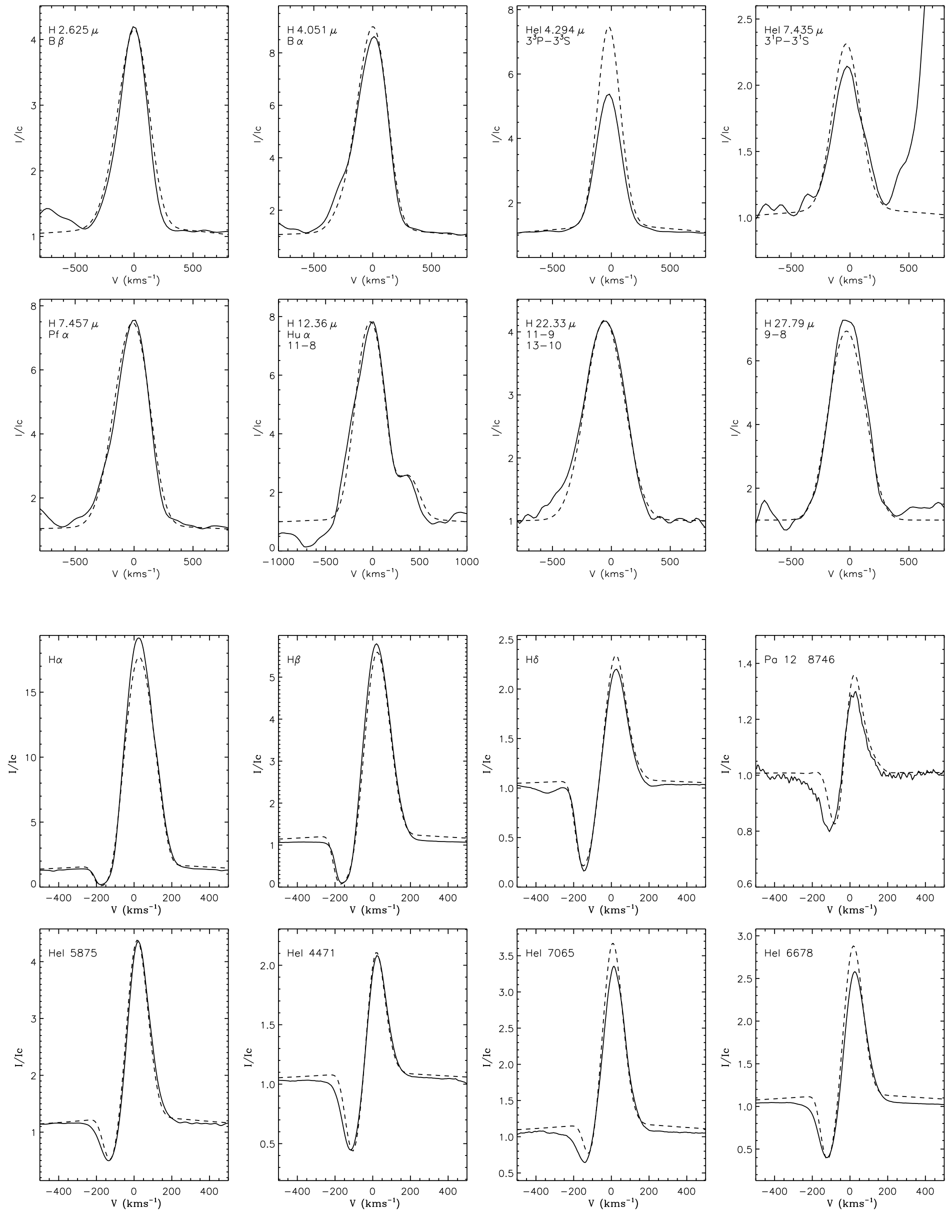

Figure 4. Top: profile fits (dashed) to the main IR H and He I lines of P Cygni observed with ISO–SWS (solid). Computed profiles have been degraded to the corresponding instrumental resolution. Each profile is labelled with the contributing component(s). Hydrogen-profile fits include the corresponding He I components (see text). Bottom: fits to the averaged optical H and He I lines.

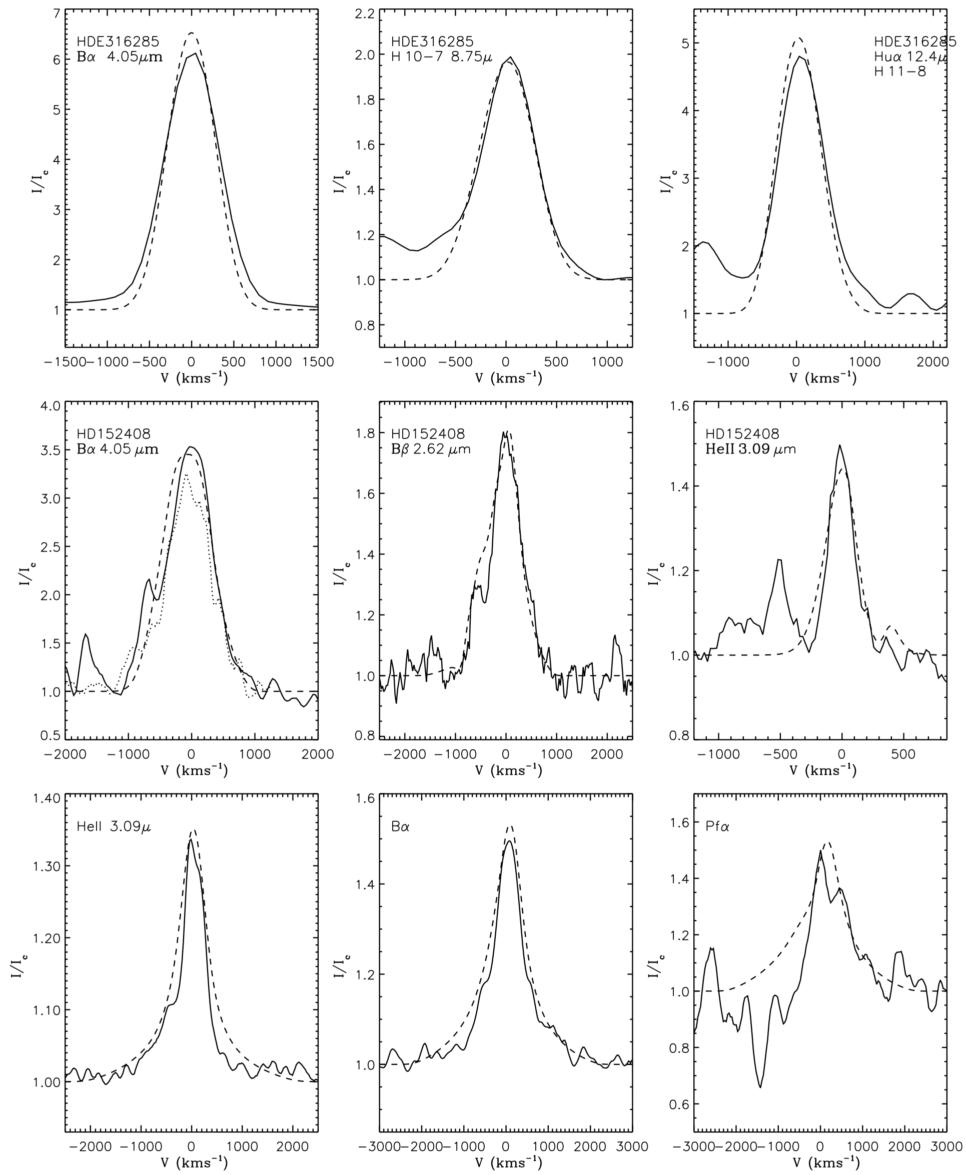

Figure 5. Profile fits to the main H and He I lines observed with ISO–SWS. Top, HDE 316285; middle, HD 152408; bottom, HD 210839.

Table 2. Preliminary stellar parameters derived for HDE 316285, HD 152408, and HD 210839 from ISO–SWS observations. Stellar parameters are consistent with those obtained from optical studies (see text).

Model	R_* ($R_\odot$)	L_* ($L_\odot$)	$T_{\rm eff}$ (10^4K)	$n_{\rm N}/n_{\rm H}$	$\dot M$ ($M_\odot$ yr^{-1})	v_∞ (km s^{-1})	β
HDE 316285	75	2.8×10^5	1.53	0.67	2.4×10^{-4}	410	2.5
HD 152408	33	6.1×10^5	2.80	0.55	2.4×10^{-5}	955	1.25
HD 210839	19	6.6×10^5	3.77	0.125	5.3×10^{-6}	2250	1.3

HDE 316285, SWS-01 ($R \simeq 800$) observations were obtained for the full SWS range. Since HD 152408 and HD 210839 are relatively weak sources for SWS we observed only the full first SWS band (2.38–4.1μm) with SWS-06 and the strongest lines in band 2 (i.e., Pfα). Data reduction was as described by Lamers, Morris, et al. (1996).

Table 2 shows stellar parameters derived from a preliminary investigation of these objects. Fits to the observed profiles are shown in Figure 5. *Our results based in ISO–SWS observations confirm those obtained from optical studies* (e.g., Crowther & Bohannan 1997 for HD 152408; Puls et al. 1996 for HD 210839; and own analysis for HDE 316285). The above result is extremely important, not only because we are able to reproduce the stellar spectra from the UV to the IR, but also as it provides us with an important degree of confidence to carry out infrared quantitative spectroscopy when, for instance, due to high extinction only this spectral region is accessible.

HD 210839, HD 152408, and HDE 316285 are the first objects in our long list of early-type stars from O6 to A3 that will be observed by ISO, which is, indeed, providing new, crucial insights in quantitative infrared spectroscopy.

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Discussion

Langer: You seem to get very large values for the acceleration parameter, β, in the B hypergiants. Is that something you expect from radiation-pressure theory?
Najarro: We carried out an investigation for P Cygni, with Adi Pauldrach's code, and the velocity structure I was getting from the spectroscopic analysis was more or less the same as he was getting from the multi-line models. It's a pretty flat velocity law, and can be approximated with such a β value.
Kudritzki: When you include the ISO infrared, it goes the other way round; the exponent becomes smaller than you might expect from wind models
Najarro: Yes, in the case of P Cyg. But when you use Adi's models you get very similar results.
Kaper: It looks like not only β, but also v_0 has decreased dramatically, from something like 80 km s^{-1} if you use only optical data?
Najarro: The reason for that large value was the high members of the Paschen series, which were observed to have high-velocity absorption dips. One way to explain that was to have the high transition velocity between wind and photosphere.
Walborn: With regard to λ Cep, the reason for the classification that you quote, O(n)fpe, was exactly for the reason of the peculiar profiles; ζ Pup is another example. Those stars (the class Conti called Oef) have reverse λ4686; also, as a class they have broadened absorption lines – rapid rotation. Additionally, the profiles tend to vary, so the timing of your observations may be important.
Najarro: Yes, that's true. As far as I remember, it's only ever been observed once that the red peak was higher than the blue peak in λ4686 for λ Cep.
Owocki: These models are still one-dimensional, right? You haven't been able to investigate rotational effects?
Najarro: That's right.