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ISO-SWS observations of Herbig Ae/Be stars: HI recombination lines in MWC1080 and CoD -42° 11721*

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Abstract. ISO-SWS grating spectra are obtained towards the two Herbig Ae/Be stars MWC1080 and CoD -42° 11721, showing hydrogen recombination lines of the Brackett, Pfund and Humphreys series. The observed line decrements in each spectral series are consistent with emission from ionized winds, as expected from these early-type stars. We compare the observed line emission with a wind model assuming a constant rate of mass flow from the star, which allows to consistently derive mass loss rate and distance of both stars. We also show that the observed decrements can only be explained by assuming a ionization bounded compact regions whose sizes are a few tens of the stellar radii.

Key words: stars: pre-main sequence – circumstellar matter – stars: mass-loss – stars: individual: MWC1080 – stars: individual: CoD -42° 11721 – infrared: stars

1. Introduction

Pre Main Sequence stars are characterized by the presence of strong, ionized winds that are the main mechanism through which the parent dense envelopes are swept out. Given the relatively high visual extinction which characterizes these early type stars, the analysis of infrared HI recombination lines is one of the main diagnostic tools to derive key parameters of the winds, such as the mass loss rate and the number of ionizing photons, which are directly linked to the star properties and its evolutionary status (see *e.g.* Simon et al. 1983, Evans et al. 1987, Nisini et al. 1995). However, any model for the emission of HI recombination lines from ionized moving envelopes relies on a number of parameters which cannot all be constrained by using only the limited number of lines accessible from the ground, especially when the star spectral type and distance are poorly known.

The most widely adopted procedure to derive information from the usually observed lines (which are commonly limited to Brγ, Brα and Pfγ), is to use the line ratios to check for optically thick effects in the line emission due to the presence of dense winds and to derive the wind mass loss rate from the line absolute intensities, on the main assumption that the wind is completely ionized, and adopting a gas velocity law. This procedure can, however, lead to inaccurancies if these assumptions are not correct. For example, it has been found that winds in low luminosity stars are mostly neutral, and therefore the mass loss rates derived assuming full ionization can be heavily underestimated (Natta et al. 1988).

In this contribution we will show how the observation of many HI lines from several different spectral series, now possible with the ISO spectrometers, allows a better definition of the physical model for their emission. In particular, the aim of this study is to show how the analysis of the line decrement in the same spectral series can give complementary information which is fundamental for a correct interpretation of the observed lines. We present the spectra of two Herbig Ae/Be stars: MWC1080 and CoD -42° 11721, which have both an early spectral type relative to the majority of the Herbig Ae/Be stars and a luminosity high enough to produce a detectable ionized region. Moreover, they also have other observed HI recombination lines, both optical and near IR, useful to complement our study.

2. Observations and results

Observations have been carried out with the Short Wavelength Spectrometer (SWS) (de Graauw et al. 1996) on-board the Infrared Space Observatory satellite (Kessler et al. 1996). AOT01 full grating scan observations at speed 2 (wavelengths 2.3÷45 μm, resolution $\lambda/\Delta\lambda$ ~250) were obtained towards CoD -42° 11721 (16h 55m 33.8s -42° 37' 37", B1950) and MWC1080 (23h 15m 14.6s +60° 34' 19", B1950) during revolutions 84 and 263 respectively. Raw data were processed using standard ISO-SWS reduction procedures (pipeline version 5.1). The additional analysis consisted of removing the spurious signals due to cosmic ray impacts, rescaling the detector scans to each other to reduce the noise due to uncertainties in the flux calibration

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Table 1. Observed line fluxes in CoD -42° 1172 and MWC1080. For lines with S/N<3 3σ upper limits are considered.

line id.	λ_{obs}	F $\pm\Delta$F
CoD -42° 11721		
line id.	λ_{obs}	F $\pm\Delta$F
	μm	10^{-18} W cm^{-2}
Brα	4.05	2.06 $\pm$ 0.06
Brβ	2.62	2.44 $\pm$ 0.09
Pfβ	4.65	0.79 $\pm$ 0.15
Pfγ	3.74	0.75 $\pm$ 0.07
Pf10	3.04	0.48 $\pm$ 0.06
Pf11	2.87	0.68 $\pm$ 0.08
Pf12	2.76	0.57 $\pm$ 0.09
Pf13	2.67	0.53 $\pm$ 0.09
Pf14	2.61	0.56 $\pm$ 0.12
Pf15	2.56	0.60 $\pm$ 0.04
Pf16	2.53	0.58 $\pm$ 0.02
Pf17	2.50	0.36 $\pm$ 0.05
Pf18	2.47	0.31 $\pm$ 0.05
Pf20	2.43	0.31 $\pm$ 0.05
Huδ	5.13	0.46 $\pm$ 0.11
Hu11	4.67	<0.80
Hu12	4.38	<0.56
Hu13	4.17	<0.71
Hu14	4.02	0.28 $\pm$ 0.08
Hu15	3.91	0.18 $\pm$ 0.06
Hu16	3.82	0.28 $\pm$ 0.09
Hu18	3.69	0.33 $\pm$ 0.12
MWC1080		
line id.	λ_{obs}	F $\pm\Delta$F
	μm	10^{-18} W cm^{-2}
Brα	4.05	0.69 $\pm$ 0.09
Brβ	2.63	0.49 $\pm$ 0.10
Pfγ	3.74	<0.18
Pfδ	3.30	0.19 $\pm$ 0.04
Pf10	3.04	0.19 $\pm$ 0.03
Pf11	2.87	0.18 $\pm$ 0.03
Pf12	2.76	<0.29
Pf13	2.67	<0.12

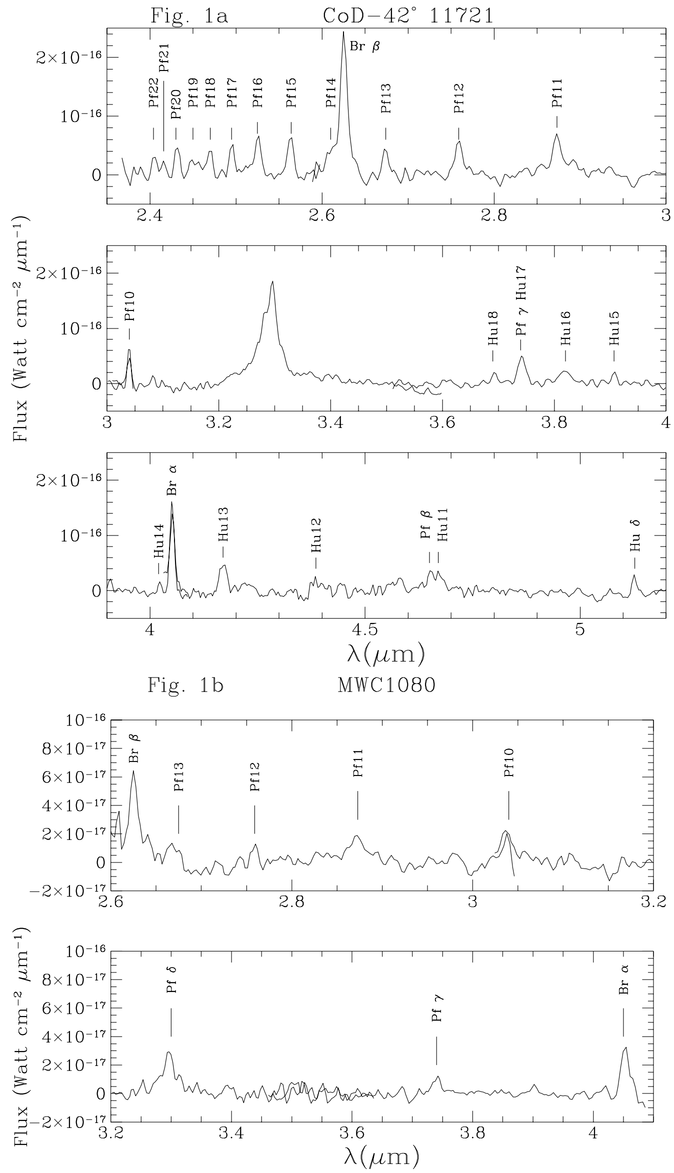

Fig. 1a and b. The continuum subtracted spectra and line identifications in the wavelength ranges in which HI lines were detected (Fig. 1a for CoD -42° 11721 and Fig. 1b for MWC1080).

and rebinning the data at twice the instrumental resolution. The above analysis has been separately carried out for the two different scan directions and the two final spectra were averaged.

Fig. 1 shows the continuum subtracted part of spectra in which the HI lines have been identified, while Table 1 lists the measured line fluxes. The uncertainty due to the flux calibration is about 30% (Schaeidt et al. 1996) and the FWHM is compatible with the nominal resolution as the lines are not spectrally resolved. The spectrum of CoD -42° 11721 is strongly dominated by broad features of PAHs, which often make it impossible to detect lines otherwise expected to be strong, like the Pfδ at 3.297 μm.

3. Comparison with wind models

3.1. The model

The observed HI line emission has been compared with a wind model which considers a spherically symmetric and fully ionized envelope where the gas is moving with a constant rate of mass loss ($\dot{M} = 4\pi r^2 \rho(r) v(r)$). The gas is assumed to have a constant temperature of 10^4 K and to be in LTE; the adopted gas velocity law is:

$$v(r) = v_i + (v_{max} - v_i)[1 - (r_*/r)^\alpha] \quad (1)$$

where v_i=20 km s^{-1}, v_{max} is the maximum wind velocity (derived from the Hα observed profiles), and r_* is the stellar radius. By increasing the parameter α, the radius at which the gas velocity approaches its maximum value v_{max} decreases. A detailed discussion on the validity of the model assumptions for the analysis of ionized winds in Herbig Ae/Be stars, is given in Nisini et al. (1995).

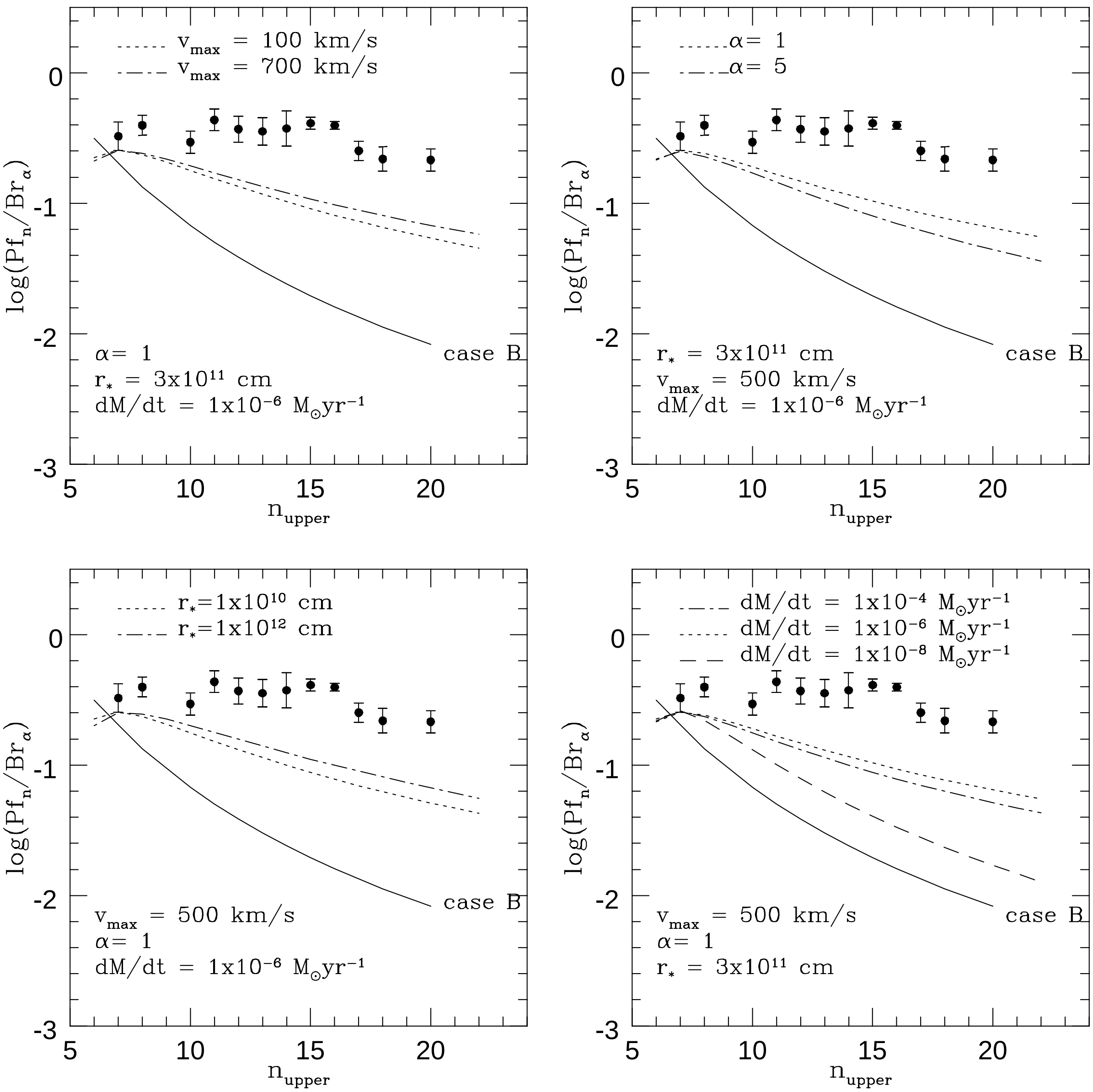

Fig. 2. The Pfund line ratios with respect to the Brα line predicted in a density bounded ionized flow (fully ionized envelope) are compared with the ratio observed in CoD -42° 11721 (filled dots) for different model parameters values. Case B recombination, for $T_e=10^4$ K and $n_e=10^4$ cm^{-3}, is also shown (Hummer & Storey 1987).

Table 2. Model paramaters of the best fit.

Object	α	A_V (mag)	r_* (cm)	v_{max} (km s^{-1})	$\dot{M}$ ($M_\odot$ yr^{-1})	D (pc)	R	Sp.T.
CoD -42° 11721	1	7.1	$3\cdot10^{11}$	500	$(3\pm1)\cdot10^{-6}$	500±100	12±2	B4-B5
MWC1080	1	5.4	$3.2\cdot10^{11}$	400	$(5\pm3)\cdot10^{-6}$	2100±600	33±9	B0

An important parameter to be considered is the amount of extinction for which the line fluxes need to be corrected. The adopted extinction law is that of Rieke & Lebofsky (1985). CoD -42° 11721 has an estimate visual extinction (A_V) ranging from 5 mag (Mc Gregor et al. 1988) to 7 mag (de Winter & Thé 1990), while for MWC1080 a value of 5.4 mag has been determined (Cohen & Kuhi 1979). To account for the A_V indetermination, we checked that, changing A_V by a factor of two, the observed line ratios in the wavelength range we are considering do not change significantly.

We first compared the observed line ratios in a given recombination series (line decrement) with the standard model in

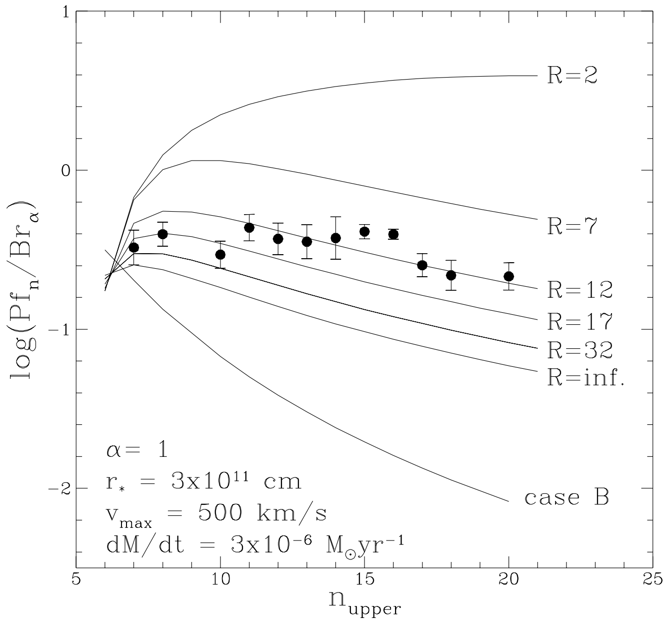

Fig. 3. Comparison between the Pfund line ratios with respect to the Brα line, as observed in CoD -42° 11721 (filled dots) and the predicted line ratios (solid lines) for different dimensions of the ionized region (R=r_{rec}/r_*); the model adopted parameters are indicated in the figure.

which the envelope is completely ionized (density bounded ionized flow). In Fig. 2 we show the behaviour of the Pfund series decrement as a function of the different parameters. It turns out that the decrement does not change very much by varying any of the considered parameters, with the only exception being the mass loss rate; for very low values of $\dot{M}$ all the lines become optically thin and then their ratios approach the Case B values (Hummer & Storey 1987). In any case, the higher lines in each series are more sensitive to variations in the model parameters than the lower lying lines.

The ratios observed in CoD -42° 11721 are much above the Case B line ratios, which means that optical depth effects start to play a significant role. They are however also in disagreement with the wind model predictions, independently of the choice of the input parameters. We have therefore modified the assumption of a fully ionized envelope by introducing, as a separate parameter, the relative physical dimension of the ionized region (R=r_{rec}/r_*), where r_{rec} represents the radius at which the hydrogen atoms recombine. Fig. 3 shows how the line decrement significantly changes with this parameter. The behaviour of the line ratios decrement is essentially due to the different optical depths in the lines. For very small values of R, the lines are all emitted from the same optically thick surface and the emission can be approximated as proportional to S(ν)·R^2, with S(ν) the Planck function at T_{gas}. As R increases, the external part of the envelope starts to be optically thin and the line emission become proportional to S(ν)·$R^2_{\tau=1}$, where $R_{\tau=1}$ is the radius at which the optical depth approaches unity (Smith et al. 1987, Simon et al. 1983). This radius depends on the transition and it is therefore different for the lines of the same spectral series; this is the reason why the line decrement slope changes with the dimension of the ionized region. The ratios observed in CoD -42° 11721 are much better fitted with models which assume a relatively small dimension of the ionized region (ionization bounded flow).

From the line decrement we can constrain the mass loss rate and the ionized region dimension; the distance to the star (D) is then derived from the absolute line fluxes. Table 2 summarizes the model parameters of the best fits for the two stars; the errors quoted for the three considered parameters are derived by taking into account the spread in the line ratios of the different decrements. In the following sections we discuss separately the results obtained.

3.2. CoD -42° 11721

CoD -42° 11721 is an emission line star embedded in a diffuse nebulosity whose physical parameters are rather uncertain, mainly because its distance is poorly known. Indeed, distance estimates range between 2600 pc (Brooke et al. 1993) and only 220 pc (Pezzuto et al. 1997); in turn the estimate of the spectral type ranges between O9 and B8. Hα emission is observed towards the source, with a FWHM of $\sim$ 500 km s^{-1}, indicating the presence of a strong wind (Hutsemekers & Van Drom 1990). Because of the lack of a defined estimate of the spectral type and luminosity of the star, its stellar radius is also not known a-priori. We have assumed a radius of $3{\cdot}10^{11}$ cm (considering that the model, as shown in Fig. 2, does not strongly depend on this parameter), and checked a posteriori that this value is consistent with the physical quantities derived by our fit. The visual extintion towards the source has been taken equal to 7.1 mag (de Winter & Thé 1990).

We have already shown that the line decrements for this star suggest a very compact ionized region (R=12$\pm$2) with a rather high rate of mass loss ($\dot{M}$=(3$\pm$1)·10^{-6} $M_\odot yr^{-1}$). In Fig. 4a we show the best fit to the data for the line ratios of Brackett, Pfund and Humphreys series with respect to the Brα line and in Fig. 5a the predicted absolute line fluxes are compared with the observed ones. The estimated distance is 500 pc; at this distance the star luminosity is $\sim 10^3$ $L_\odot$, which indicates a spectral type B4 - B5. These estimates of distance and spectral type are in agreement with those found by Pezzuto et al. (1997) by fitting the continuum emission of the source.

Emission from the Brackett series was observed by McGregor et al. (1988), who estimated from the Brγ luminosity a mass loss rate $> 5{\cdot}10^{-6}$ $M_\odot yr^{-1}$, positioning the star at D>2000 pc and assuming a fully ionized envelope model. They however do not check for the consistency of their derived parameters with the observed Brackett line decrement; their measured lines in the Brackett series agree with the model we derive from the SWS data (Fig. 4a).

3.3. MWC1080

MWC1080 shows Hα emission with strong P-Cygni profile, indicating a wind with velocity of $\sim$ 400 km s^{-1} (Finkenzeller & Mundt 1984). The spectral type is estimated to be B0 and

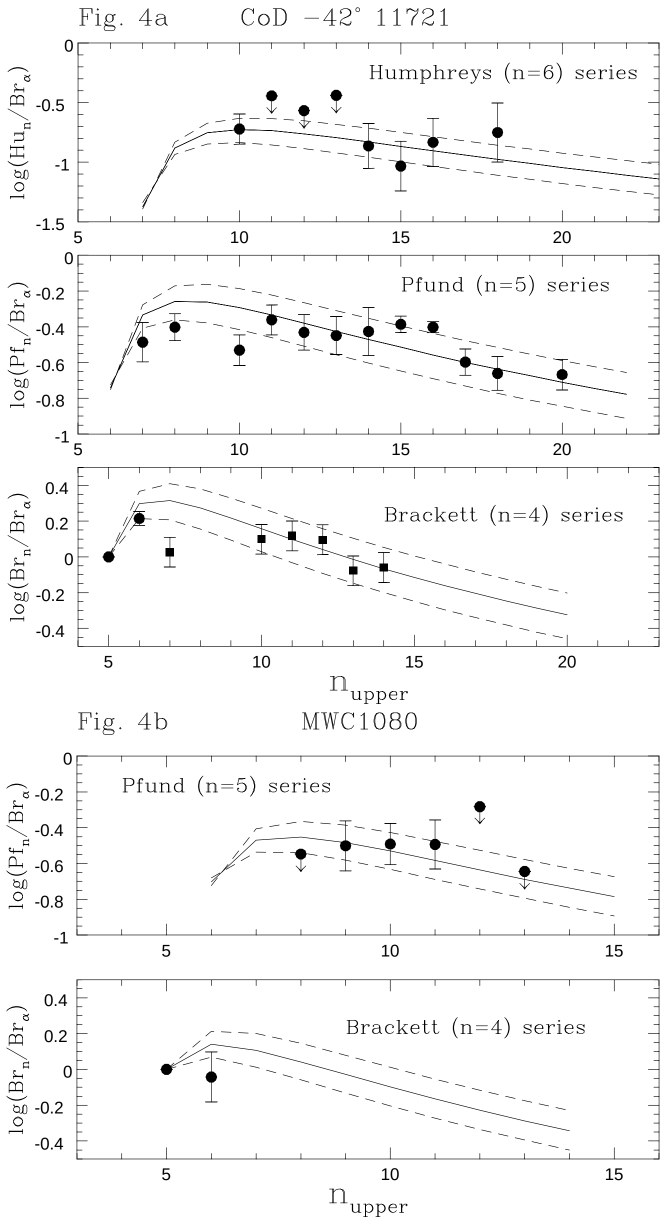

Fig. 4a and b. Best fit of our wind model to the data (solid line). Filled dots are the line ratios of Brackett, Pfund and Humphreys series with respect to the Brα line as observed in CoD -42° 11721 (Fig. 4a) and in MWC1080 (Fig. 4b); arrows are 3σ upper limits. Dashed lines delimit the range of models considered for the evalutation of the parameter errors. In Fig. 4a filled squares in the Brackett series diagram indicate the line ratios observed by McGregor et al. (1988).

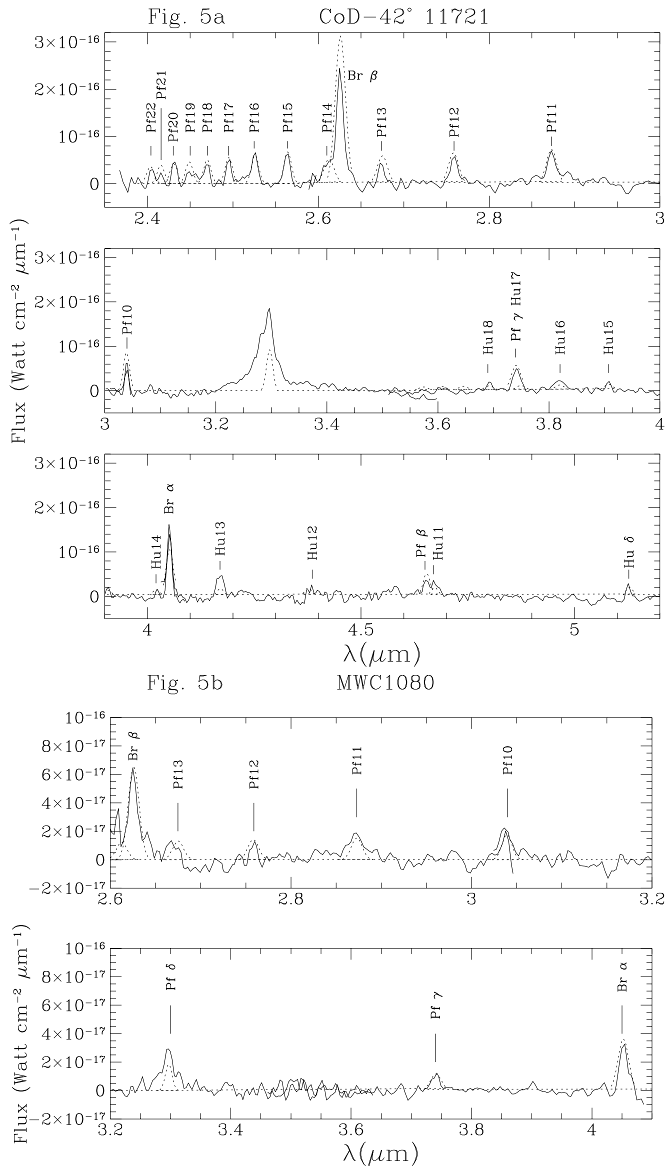

Fig. 5a and b. Comparison between observed spectra (continum line) of CoD -42° 11721 (Fig. 5a) and MWC1080 (Fig. 5b) and our best model predicted line fluxes (dotted lines).

the distance ranges between 1000 pc (Hillenbrand et al. 1992) and 2500 pc (Cantó et al. 1984). This source drives a powerful molecular outflow from which a wind mass loss rate of about 4$\cdot$10^{-6} M$_{\odot}$yr^{-1} has been derived. From the absolute flux of some recombination lines, Nisini et al. (1995) find a wind mass loss rate in agreement with this value.

We have assumed an A_V=5.4 mag (Cohen & Kuhi 1979) and a stellar radius of 3.2$\cdot$10^{11}cm (Nisini et al. 1995). Also in this case the ionized region has a finite size of (33$\pm$9)r$_*$. Despite that, the derived mass loss rate ((5$\pm$3)$\cdot$10^{-6}M$_{\odot}$yr^{-1}) is consistent with that computed assuming a fully ionized envelope. At our estimated distance of 2100 pc, the star has a luminosity of $\sim$10^4 L$_{\odot}$ and a B0 spectral type, confirming the values quoted in Berrilli et al. (1992). The comparison between the observations and the model are shown in Fig. 4b for the line ratios of Brackett and Pfund series with respect to the Brα line and in Fig. 5b for the absolute line fluxes.

4. Discussion

The effect of a ionized bounded region on the line ratios in moving envelopes was first discussed by Simon et al. (1983) who showed that the ratios of infrared lines usually observed from the ground (like Brγ and Pfγ) can have a wide range of values depending on the external radius of the region, until an asymptotic ratio is reached for large values of the R parameter. They predicted that if the source had detectable radio emission, the asymptotic value of the line flux ratio is surely reached, since the radio continuum flux is very sensitive to the ionized region dimension and a too small optically thick region would produce negligible radio emission. Both CoD -42° 11721 and MWC1080 have been observed in the radio by Skinner et al. (1993) who did not detect any appreciable 3.6 cm flux for the two stars. In particular CoD -42° 11721 was considered an undetected star with a quite high 3σ upper limit due to a bright extended radio source near the star. For MWC1080 a flux $S_{3.6cm}$=0.18 mJy was detected but this emission does not coincide with the star optical coordinates and, moreover, is a factor 5 less than the emission predicted for a density bounded ionized envelope (Nisini et al. 1995).

We checked the consistency of our derived parameters by comparing the expected ionizing photon flux from the two stars, given our estimated spectral types, with the assumption of ionized bounded regions. From Felli & Panagia (1981) the number of recombinations per unit time in the total envelope is:

$$N_L = N_{LO} f(\gamma, v_i/v_{max}) \quad (2)$$

where

$$N_{LO} = \frac{1.2 \cdot 10^{48}}{1+2\gamma} \left(\frac{\dot{M}}{10^{-6} M_\odot yr^{-1}}\right)^2 \left(\frac{100 kms^{-1}}{v_i}\right)^2 \times \times \left(\frac{3 \cdot 10^{11} cm}{r_*}\right) \left(\frac{10^4 K}{T}\right)^{0.8} s^{-1} \quad (3)$$

and

$$f(\gamma, v_i/v_{max}) = 1 + 2\gamma (v_i/v_{max})^{\frac{1+2\gamma}{\gamma}} \quad (4)$$

for a velocity varying as $v_i(r/r_*)^\gamma$ until a velocity v_{max} is reached and then becoming constant. With our velocity law, the factor $f(\gamma, v_i/v_{max}) \sim 1$ so N_{LO} is an excellent estimate of the number of UV photons required to fully ionize the flow to infinity. We estimate $N_{LO} \sim 9{\cdot}10^{49}$ s^{-1} for CoD -42° 11721 and $N_{LO} \sim 2{\cdot}10^{50}$ s^{-1} for MWC1080. These values have to be compared with the continuum Balmer luminosity supplied by a B5 or B0 star which are 10^{47} s^{-1} and $7{\cdot}10^{48}$ s^{-1} respectively (Thompson 1984). Hence, the stars do not have enough UV photons to ionize the flow to infinity, consistently with our estimated small size of the ionized region.

5. Conclusions

We have presented the detection of several HI recombination lines from the Brackett, Pfund and Humphreys series towards the two Herbig Ae/Be stars CoD -42° 11721 and MWC1080, obtained with the Short Wavelength Spectrometer on-board ISO. These lines have been analyzed adopting an ionized wind model; the conclusions from this analysis are the following:

- all the observed line ratios are higher than expected from optically thin recombination, but they are also higher than those predicted by common wind models which assume a density bounded ionized region. This discrepancy is more evident for the higher lines of each series;

- the observed line decrements can instead be explained by assuming that the star does not have enough UV photons to ionize the envelope entirely and that the photons are all absorbed in the inner, high optically thick part of the wind. The data are well fit by ionized regions extending only a few stellar radii;

- with the above assumption, from both the line ratios and the absolute intensities, we consistently derive the mass loss rate, the dimension of the ionized region and the distance to the two stars.

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