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Wind variability in central stars of planetary nebulae. II.

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Abstract. New high resolution IUE spectra of central stars of the planetary nebulae (CSPN) NGC 40, NGC 6543, NGC 6826, and BD +30 3639 have been obtained between August 1994 and September 1995 to explore the variability of their P Cygni profiles. The data have been analyzed together with previous observations of the same stars. Significant changes in the profiles of several of the typical wind lines of the N V, O IV, O V, Si IV, C IV, and N IV ions have been revealed in all the observed stars. By combining these results with the ones obtained in a previous paper of this series (Patriarchi & Perinotto 1995; Paper I), it is found that half of the fourteen observed CSPN exhibit changes in the shape of their P Cygni profiles up to levels of $10-50\%$ in timescales of years, analogous to similar timescale variations exhibited by hot stars of population I. They are: NGC 40, NGC 1535, NGC 2392, NGC 6543, NGC 6826, IC 4593 and BD + 30 3639. The ones for which changes have not been detected are: NGC 246, NGC 6210, NGC 6572, NGC 7009, IC 418, IC 2149 and Lo 8. The present paper completes the survey of this type (at least $2-3$ well separated high resolution good exposures for each star) that could have been done in central stars of planetary nebulae using the IUE satellite. In a typical case (NGC 1535) we estimate that the changes in the physical properties of the wind, resulting from the observed changes in the P Cygni profiles, amount for $\dot{M}q_{\rm NV}$ to a factor of 3 ± 1.

Key words: planetary nebulae: general — stars: mass loss

1. Introduction

The variability in the shape of P Cygni line profiles is important in connection with the mechanisms responsible for the wind production and for the constancy of the associated mass loss rates. Comprehensive studies of these changes have been made with the IUE satellite in population I OB stars, showing that essentially all the studied stars exhibit variability in their P Cygni profiles at various timescales from minutes to years (cf. Baade 1988; Henrichs 1988). Recently Kaper et al. (1996) have performed an extensive study of ten bright O stars covering a long time interval (1986 – 1992) with observations spanning time intervals from days to hours, using simultaneous IUE and ground based high resolution spectroscopy, photometry, and polarimetry. Particularly significant was the discovery that the Discrete Absorption Components (DAC) phenomenon is very general in population I O stars and practically ubiquitous. The accurate description of the dynamics of the DAC led the authors to stress the likely importance of the stellar rotation in influencing the structure of the winds.

On the other hand the problem of wind variability in hot evolved stars, particularly in CSPN, has received little attention so far. This in spite of the fact that the fast winds in CSPN are recognised, according to the multiple wind theory (Kwok et al. 1978; Kwok 1987; Khan 1989), to be essential for the formation and the evolution of the observed nebulae. The relevant information is contained in the SWP spectral range of the IUE satellite. A first effort in this direction was made by Patriarchi & Perinotto (1995, hereafter Paper I), who studied all the available good quality IUE high resolution SWP spectra (14 objects). Variations in P Cygni lines up to 50% in the shape of the profiles over time scales from months to years was revealed in four out of the fourteen observed objects, while in NGC 6543 photometric variability was suggested. Particularly remarkable was the lack of variations in the two pure WR stars contained in the sample of the Paper I (NGC 40 and BD +30 3639).

The database used in Paper I was, unfortunately, not so rich since in most cases only 2-3 epochs were covered.

With the present paper we contribute new high resolution IUE observations of NGC 40, NGC 6543, NGC 6826, and BD +30 3639. In Sect. 2 the observational data and the method of analysis are presented, while the results are given in Sect. 3. The discussion follows in Sect. 4.

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Table 1. High resolution IUE spectra of central stars of PNe

Name	Sp. type	SWP	Date	Time hh:mm	Exp min	Variat.* detected
NGC 40	WC8 (1)	51880	22 08 1994	18:30	135	YES
		52744	06 11 1994	12:50	328	
NGC 6543	OfWR(H) (1)	51881	22 08 1994	23:16	80	YES
		55982	21 09 1995	20:20	115	
NGC 6826	O3f(H) (1)	51871	21 08 1994	22:53	115	YES
		55981	21 09 1995	15:50	120	
BD+30 3639	WC9 (1)	51870	21 08 1994	18:34	170	YES

1. Mendez (1991).
* YES means a detection of variability considering either the spectra reported here and/or spectra studied in Paper I (see text).

2. Observations and data analysis

New high resolution SWP IUE spectra of NGC 40, NGC 6543, NGC 6826, and BD +30 3639 have been obtained during 1994 and 1995 under the proposal RA090. The observational data are reported in Table 1.

The original spectral resolution is about 0.10 Å. As discussed in detail in Paper I, the wavelength calibration error of the reduced spectra is of ± 25 km/s, while the flux calibration error is of about 4% (1σ) longward of λ1400 Å and of about 6% shortward of λ1400 Å. This applies to the high resolution SWP images taken after November 10, 1981 at the Goddard Space Flight Center and after March 11, 1982 at VILSPA. For the high resolution images before these dates, the calibration function of Cassatella et al. (1981) is used. In this case the errors are of 5% and 8% for wavelenghts longward and shortward of λ1400 Å, respectively.

Considering that the reproducibility limit of IUE is of 6% at 2 σ level (Bohlin et al. 1980), we accept that changes by more or equal 10% indicate true variations in the spectra to a 3 σ level.

To search for variations in the lines profiles and/or in the continuum, the following procedure has been used. The total number of the available spectra in each object, including those listed in Paper I, have been averaged. Each spectrum has then been rescaled to the average spectrum by a factor, which, if different from 1, reveals the existence of changes in the level of the continuum. These changes refer to the whole spectrum and can be called "photometric" variations. By comparing the rescaled spectra in the regions of the relevant spectral lines, one can detect changes of the line profiles. When a variation, photometric or affecting a line profile, is larger than 10%, we conclude that the change is real.

To reduce the noise, preserving however the shape of the real spectral features, i.e. without degrading the actual spectral resolution, we did apply a smoothing procedure. This was possible taking advantage of the oversampling of about 5 times the spectral resolution, performed by IUESIPS (IUE Spectral Image Processing System).

After the filtering, some residual artifacts from cosmic rays and from the reseau marks remain. They have been identified and made evident with crosses in the figures, using the quality factor parameter. We thought this is safer than to remove them from the spectra with interpolation procedures.

The spectral intervals considered to compare line profiles were of ± 20 Å around the mean wavelength of the most conspicuous P Cygni lines known to occur in CSPN in the UV range: $\lambda\lambda$ N V 1238.82, 1242.80; O IV 1338.60, 1342.98, 1343.51; O V 1371.29; Si IV 1393.73, 1402.73; C IV 1548.20, 1550.77; N IV 1718.55 Å.

We have examined with the above procedure the new spectra reported in Table 1 and all the spectra listed in Paper I of the same four stars. Note that in Paper I we did not compare to each other "adjacent" spectra, i.e. spectra taken within the same IUE shift, considering that their separation being of the same order of the lenght of the exposures, hardly changes could have been revealed between them. Anyhow not to lose this possibility, we have now included in the analysis all the available individual spectra of the four stars under study.

As with the minimum detectable variation in the edge velocity of the P Cygni lines, we judge that in the spectra of our stars it amounts to ± 30 km/s, where the "edge velocity" corresponds to the blue border of the observed profile.

In the last column of Table 1 we report where variations have been seen. This takes into account also the spectra considered in Paper I.

Details on their nature and amount are given in the next section.

3. Results

We present the results object by object, describing the photometric variations and illustrating with figures only the profiles where variations have been detected. No variations have been seen in the available spectra within the timescale of hours. Given the duration of the exposures, it is however evident that only markedly large changes could have been revealed this way.

To better illustrate the flux variation in the spectra we present at the bottom of each figure the absolute difference between the pair of displayed spectra. Over this difference the sum of the standard deviations of the two spectra, in bins of 200 km/s is plotted. When the level of the flux difference is above this line, we can say that the two spectra differ by more than 2 σ (provided, as it is generally the case, that the noise level is similar in the two spectra). In this way one obtains a clear quantitative representation of the zones where the two spectra differ.

In Table 2 for each pair of considered spectra the presence or not of variability is reported. In the positive case the observed velocity range is given. These ranges in some cases indicate red-shifted motions. Most probably these variations are due to changes in the receding part of the envelope contributing to the emission peak of the profile. This might indicate an asymmetry in the CSPN's wind.

NGC 40:
In Paper I we did not see variations between the two available spectra (January 1983 and August 1991). With the addition of the new observations (August 1994 and November 1995) we see that changes did occur in the C IV line profile between the last two epochs (Fig. 2) and also relatively to the previous data (Fig. 1). Between August 1994 and November 1995 the emission peak of the C IV profile increased by 15%, while between August 1991 and August 1994 the same peak decreased by a 25%.

In conclusion in this star we observe P Cygni profiles of the following lines: N V, O V, C IV and Si IV and changes have been seen only in C IV.

NGC 6543:
In Paper I we reported variations in the regions of all the P Cygni line profiles seen in the object, i.e. the lines listed in Sect. 1. But, due to evident changes in the level of the continuum and of the technique used in that article, we had not been able to disentangle the two types of variations, i.e. the photometric ones and those affecting the line profile. Now we can separate the two kinds of variations.

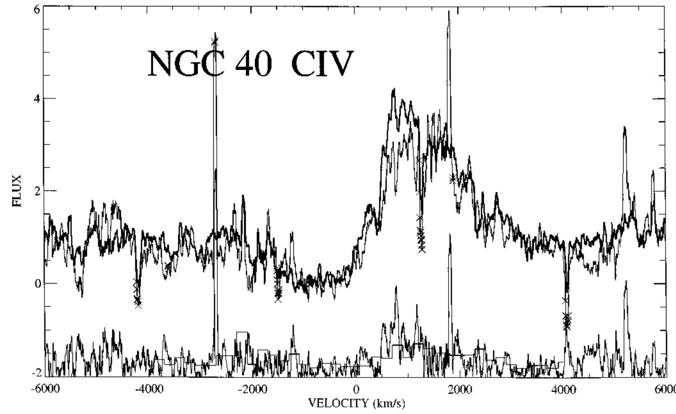

Fig. 1. NGC 40. Comparison of SWP 51880 vs. SWP 42188. The older spectrum (lower number) is plotted with the thick line. 0 km/s coresponds to the rest wavelength of the blue component of the C IV resonance doublet. In this and in all the following figures the unit of Flux is 10^{-14} erg cm^{-2} s^{-1} Å^{-1}. For the meaning of the lines at the bottom see text

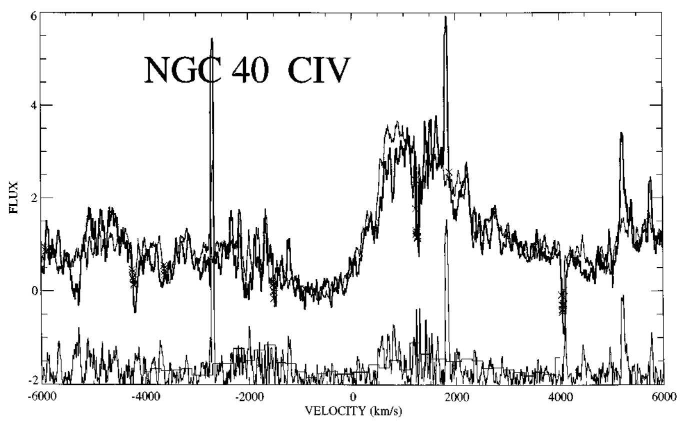

Fig. 2. NGC 40. Comparison of SWP 51880 vs. SWP 52774. The older spectrum (lower number) is plotted with the thick line

Between 1978 and 1993 we see a photometric decrease by a 15% followed by an increase of 12% between 1993 and 1994.

As with the variations in the line profiles, between 1978 and 1993 a decrease of 10% occurs in the emission peak of the C IV profile, as well as a decrease also of $v_{\rm edge}$ of 170 km/s (Fig. 3). Between 1993 and 1994 the C IV profile retains the same shape except that its edge velocity did increase by the same amount (Fig. 4). Between 1994 and 1995 the only change in the C IV profile consists again in a reduction of its $v_{\rm edge}$ by 170 km/s (Fig. 5). The last two figures can be seen as examples of profiles that do not change (neglecting the portion around $v_{\rm edge}$).

As with the O V profile, we note variations only between 1993 and 1994 (Fig. 6). These are however difficult to interpret even qualitatively.

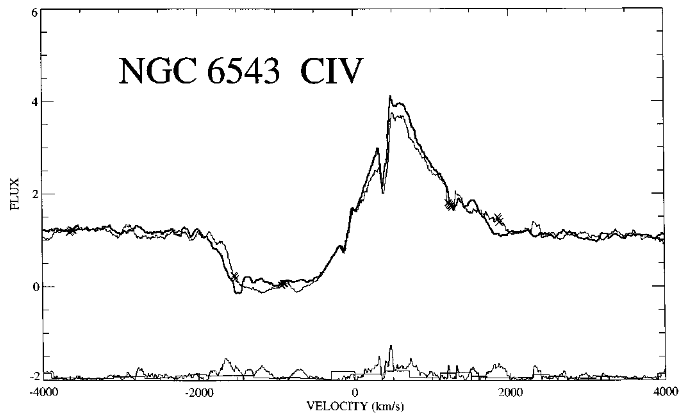

Fig. 3. NGC 6543. Comparison of SWP 3324 vs. SWP 47852. The older spectrum (lower number) is plotted with the thick line

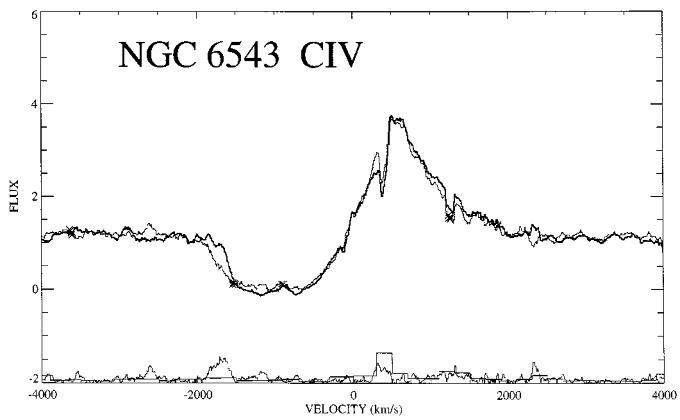

Fig. 4. NGC 6543. Comparison of SWP 51881 vs. SWP 47852. The older spectrum (lower number) is plotted with the thick line

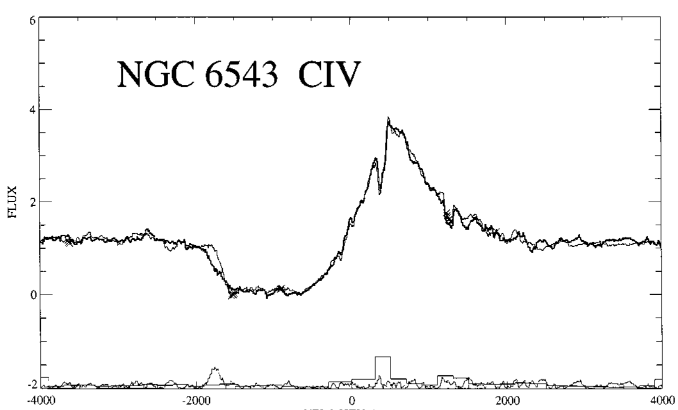

Fig. 5. NGC 6543. Comparison of SWP 51881 vs. SWP 55982. The older spectrum (lower number) is plotted with the thick line

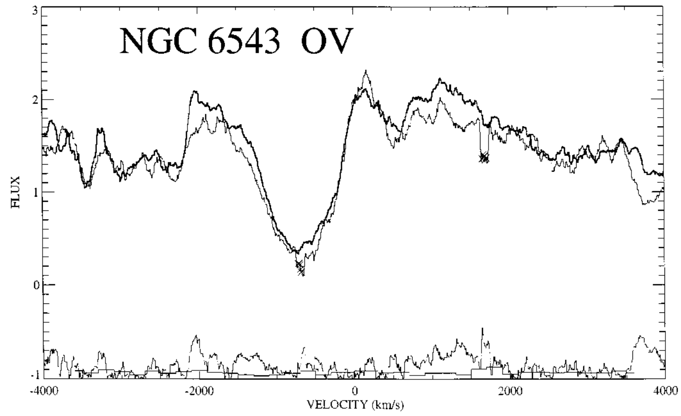

Fig. 6. NGC 6543. Comparison of SWP 3324 vs. SWP 47852. The older spectrum (lower number) is plotted with the thick line

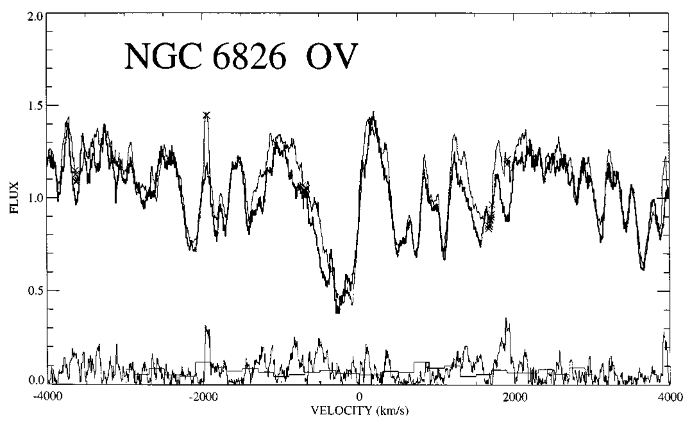

Fig. 7. NGC 6826. Comparison of SWP 20869 vs. SWP 55981. The older spectrum (lower number) is plotted with the thick line

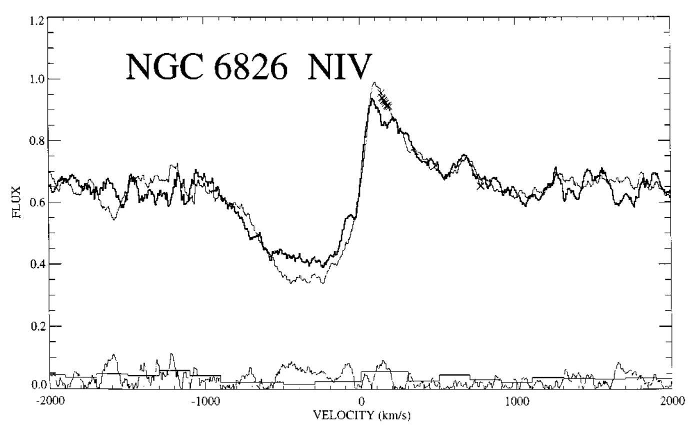

Fig. 8. NGC 6826. Comparison of SWP 51871 vs. SWP 55981. The older spectrum (lower number) is plotted with the thick line

NGC 6826:
No changes have been noted between the new spectra (August 1994 and September 1995), except for the N IV profile (Fig. 8) where differences are seen in the absorption component which became deeper by a 15%. By comparing SWP 20869 (see Paper I) vs. SWP 55981 we have between August 1983 and August 1994 a decrease in edge velocity (120 km/s) in the O V line (Fig. 7). We note that in this star changes are seen also in the subordinated lines.

BD +30 3639:
This WC star is quite rich in emission and absorption features across the whole observed IUE spectrum. P Cygni lines are seen in O V, C IV and Si IV while the wealth of the features mimics the existence of the N V and N IV lines when observed at IUE low resolution (cf. Patriarchi & Perinotto 1991).

We have compared the images SWP 13333 (see Paper I) and SWP 51870. In C IV line (Fig. 9) we observe a reduction of the emission component of the P Cygni profile of 20%.

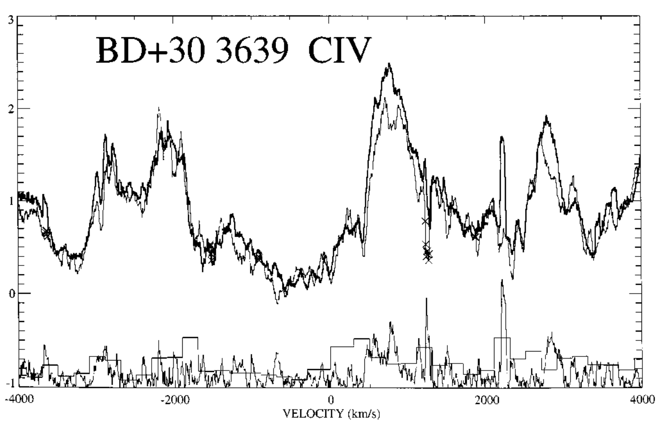

Fig. 9. BD +30 3639. Comparison of SWP 13333 vs. SWP 51870. The older spectrum (lower number) is plotted with the thick line

4. Discussion

We have seen that all the objects studied in the present paper did show changes in the shapes of one or more of their P Cygni profile up to levels of 10 − 30% over timescales of years. It is remarkable that in two (NGC 40 and BD +30 3639) out of the four stars presently studied, the addition of few spectra has led to the discovery of changes in the shapes of their P Cygni profiles, while they did not exhibit changes in the spectra available at the time of Paper I. Combining the results of Paper I with those of the present paper, we find that seven out of fourteen observed central stars did exhibit changes in their P Cygni profiles over timescales of years. They are: NGC 40, NGC 1535, NGC 2392, NGC 6543, NGC 6826, IC 4593 and BD + 30 3639. Those where changes have not been revealed are: NGC 246, NGC 6210, NGC 6572, NGC 7009, IC 418, IC 2149 and Lo 8. In NGC 1535 and NGC 6572 observations only in two epochs are available, and this is also true for NGC 246, considering that two of the three available spectra are "adjacent".

We then suspect that, if more data would have been secured, the phenomenon of the P Cygni line variability in central stars within timescale of years might have revealed to be more common than the 50% resulting from the presently available data.

4.1. Dependence on fundamental stellar parameters

We have made an effort to clarify whether the data indicate any correlation of the observed variations of the P Cygni profiles with the fundamental parameters of the stars. We did not see any indication of this type. Specifically the property "variations detected vs. variations not detected" does not exhibit any tendency to favour higher or lower values of the following parameters: $T_{\rm eff}$, $\log g$, $R/R_{\odot}$, $L/L_{\odot}$, v_{∞} of the wind.

Neither the available data suggest a tendency for objects closer to the Eddigton limit to favour the variability of the P Cygni profiles, as one might suspect. For instance the two O(H) central stars of NGC 1535 and NGC 7009 are quite close to each other in the $\log(g) - \log(T_{\rm eff})$ diagram (McCarthy et al. 1990; Mendez et al. 1988). Yet we noted variations in the first star, not in the second one. As with the two WR stars BD +30 3639 and NGC 40, according to the recent detailed study by Hamann and collaborators (see Hamann 1996), the first star is very close to the Eddington limit, while NGC 40 is quite far from it. Yet both exhibit variations in their P Cygni line profiles.

Certainly the amount of data secured, while useful to prove the existence and extent of the phenomenon, is not sufficient to clarify any possible link to the fundamental physical parameters.

4.2. Comparison with behaviour of population I OB stars

We observed variations in the edge velocity of CSPN up to about 200 km/s, i.e. 10% of $v_{\rm edge}$. This occurred in the resonance lines N V in NGC 6826 (Paper I), C IV in NGC 6543 and NGC 6826, and in the subordinate line O V in NGC 6826.

In population I OB stars velocity variations have been seen all across the wind profile, i.e. from zero velocity to the edge velocity, with shifts in velocity on a 10% level (16% in the case of HD 203064) (Kaper et al. 1996). All of them have been interpreted as manifestations of the DAC (Discrete Absorption Component) phenomenon. Due to the more pronounced saturation effects in the resonance P Cygni lines of CSPN relative to population I OB stars and to the lower signal-to-noise of CSPN spectra, we were

Table 2. Observed variability in wind lines*

Spectra	N V	O IV	O V	Si IV	C IV	N IV
NGC 40						
SWP 51880/42188	no	–	no	no	+500/+1000	–
SWP 51880/52774	no	–	no	no	+500/+900	–
NGC 6543						
SWP 3324/47852	no	no	see text	no	+200/+1000 −1900/ − 1730	no
SWP 47852/51881	no	no	no	no	−1900/ − 1730	no
SWP 51881/55982	no	no	no	no	−1900/ − 1730	no
NGC 6826						
SWP 20869/55981	no	no	−400/ − 1000	–	no	no
SWP 51871/55981	no	no	no	–	no	−600/0
BD+30 3639						
SWP 13333/51870	–	–	no	no	+500/+800	–

* In case of resonance doublet (N V, Si IV, C IV) the indicated velocity range is with respect to the rest wavelength of the blue doublet component.

not able to detect the DAC phenomenon in CSPN. We cannot then conclude whether also in the CSPN the edge velocity variations are manifestations of the DAC phenomenon.

As with variations in the intensity level inside the profiles, we observed changes from 10 to 30%. This is comparable with the analogous variations in OB stars (cf. Kaper et al. 1996). We recall however that in the case of population I OB stars, the wind variability concentrates on the absorption part of the P Cygni profiles, whereas the emission peak is constant in time.

The IUE data base does not allow to investigate whether the important smaller timescale variations (DAC) recognised to occur in all the population I OB stars are indeed present in the quite higher gravity CSPN. The new generation STIS instrument to be installed on board of HST will provide enough throughput and spectral resolution to pursue this important issue.

In conclusion we have revealed that significant variations in the shape of the P Cygni profiles over timescales of years are a common phenomenon in CSPN. But to further investigate the real meaning of these variations along the evolution history of a central star, quite more data are needed.

4.3. Effects on the mass loss rates

To examine how much the detected variations can affect the mass loss of the star we have considered the case of NGC 1535. This star has P Cygni profiles only in N V and O V (Cerruti-Sola & Perinotto 1989). While the profile of O V did not change appreciabily in the examined spectra (December 1980, March 1981), the N V profile did vary in its absorption component (see Paper I). Using the

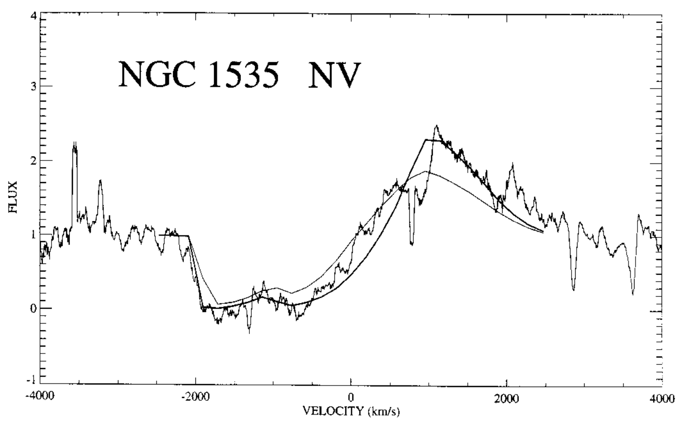

Fig. 10. SEI model fit (thick line) of SWP 13495 spectrum of NGC 1535. For the meaning of the thin line see text

SEI method (Lamers et al. 1987) we have fitted both N V profiles. From the fitting parameters we have estimated $\dot{M}q_{\rm NV}$, where $q_{\rm NV}$ is the mean ionization fraction across the wind whose mass loss rate is $\dot{M}$. The above quantity did increase by a factor 3 ± 1. This does not necessaryly imply a corresponding variation in the mass loss rate, also considering the constancy of the O V profile. In Fig. 10 the observed profile of March 1981 is compared with the best fit profile (thick line) and with a model profile obtained decreasing only the most important parameter, i.e the total optical depth in the wind, from 8 to 2 (thin line). The other parameters are: $v_\infty = 1900$ km/s, $v_{\rm turb} = 100$ km/s, $\beta = 1.5$, $\alpha_1 = 2$, $\alpha_2 = 0.5$ (cf. Lamers et al. 1987). To understand the meaning of the above result it is essential to have an accurate knowledge of the ionization structure, whose determination is quite difficult and out of the purposes of the present paper.

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