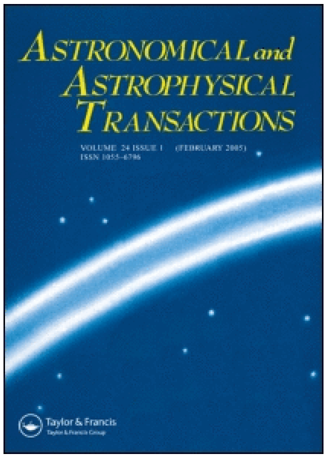

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CHANGES OF THE He II 4686 Å BROAD LINE ASYMMETRY OF NGC 4151 IN 1986–1990

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The NGC 4151 optical spectra obtained with the TV scanner of the 6-meter telescope in 1986–1990 are presented. The 4060–4860 Å spectral range was observed. The dispersion was $0.5 \div 2$ Å/channel. The characteristic signal-to-noise ratio in individual spectra was $S/N = 10 \div 25$. Spectra averaged through periods $\leqslant$2.5 months show changes of asymmetry of the He II λ4686 Å broad emission line with a characteristic timescale $\approx$2 years.

KEY WORDS Active galactic nuclei, broad line profiles, He II line variability.

1. INTRODUCTION

Researches of line profiles and continuum of active galactic nuclei (AGN) are able to supply us with important information about the emission region sizes, kinematics, and characteristics of the emitting gas (Fabrika, 1980; Blandford & McKee, 1982; Antokhin & Bochkarev, 1983; Clavel *et al.*, 1990).

The galaxy NGC 4151 is the most popular object among the investigated AGNs because of, its brightness $m_B = 11.15^m$ (Lipovetsky *et al.*, 1987), and as a result of availability for research in many spectral ranges. Variability of NGC 4151 was studied in different ranges of the spectrum. At X-ray wavelengths, an irregular behavior on a timescale of 1.4 days (Lawrence, 1980), and even more rapid flares of 700′ s duration, have been observed (Tananbaum *et al.*, 1978). Rapid and strong flare variability of NGC 4151 in X-rays was noticed also by Ulrich *et al.* (1984) and Clavel *et al.* (1987).

Variability in the UV waveband is similar to that at optical wavelengths (Perola *et al.* 1982), for which continuous monitoring at U, B and V by Lyutyi (1977) has demonstrated two characteristic timescales of 10–50 d, and 3–5 yrs., most prominent at U. Photographic B-band monitoring between 1978 Feb–1983 Mar (Gill *et al.*, 1984) indicates changes covering both of these timescales. The most rapid variations at infrared (2.2 μm and 1.6 μm) wavelengths occur typically with periods of several weeks (Penston *et al.*, 1971, 1974; Rieke & Low, 1972, 1975; Stein *et al.*, 1974).

Optical spectrum of NGC 4151 was studied repeatedly. The spectral variability of broad lines has been established on timescales of weeks, months, years, in the optical (Cherepashchuk & Lyutyi, 1973; Boksenberg *et al.*, 1975; Antonucci & Cohen, 1983) and UV (Ulrich *et al.*, 1984; Clavel *et al.*, 1990) ranges.

The very principal question is the differences of time delays in blue and red wings relative to the continuum. This is because it gives a chance to study the BLR gas kinematics. Using the IUE data for NGC 4151, Gaskell (1988) found that variations in the blue wing of C IV are delayed with respect to the red one by 3.4 ± 3.4 d., for Mg II $\lambda 2798$ Å the corresponding delay is 4.5 ± 3.1 d. This effect has a low confidential level but permits us to suggest that the gas is moving toward the center. The same conclusion follows from Clavel *et al.*'s (1990) analysis of fast variations of the line wings in comparison to the line cores.

Asymmetry observed in several broad emission lines can be variable on a timescale of 10–15 years. NGC 4151 shows a typical example for it. During 1963–65, the broad component of Hβ has a red depression (Oke & Sargent, 1968). In 1970, a strong blue depression took place (Anderson, 1970), which started to decrease in 1974 (Boksenberg *et al.*, 1975). In 1976–81 the line was almost constant, and in 1980–84 both wings were decreasing and almost disappeared in May 1984 (Lyutyi *et al.* 1984; Penston & Perez 1984). The wings appeared again in 1985 (Peterson 1985) and became sufficiently strong (Bochkarev 1987). The galaxy was actively observed during 1986–1990 on the 6-meter telescope. In 1986 strong blue wings of Hβ and Hγ were observed; in 1987 they decreased, but were restored in 1988 (Bochkarev *et al.* 1989).

Analysis of observations and model calculations of BLR gives a number of important conclusions about the structure of the nuclear region and gas kinematics. BLRs are stratified into so-called low ionization line regions (LIL), where hydrogen lines form, located in outer parts of the accretion disk, and high-ionization line regions (HIL), were He II, C IV etc, lines are emitted. These are located far from the disk plane (Collin-Souffrin *et al.* 1982, 1988), Collin-Souffrin and Dumont (1986, 1989). Therefore it is interesting to study the kinematics of the He II formation region, using long-term observations of He II $\lambda 4686$ Å wings' variations.

2. OBSERVATION DATA AND PROCESSING

Series of spectral observations of the nucleus of the Seyfert galaxy NGC 4151 was carried out using the 1024 channel TV spectral scanner of the 6-meter telescope (Drabek *et al.* 1987).

The TV scanner makes it possible to simultaneously obtain the spectra of the object, as well as an area of the night sky on two photocathode lines spaced 40″ apart. The comparison spectrum (argon-neon-helium) was also exposed on both lines. The TV scanner operates in the linear mode at counting rates of <0.5 count/channel. Nonlinear effects become noticeable at counting rates above 1 count/channel.

The observations were made with a rectangular aperture of 1″ width and 4″ height, which corresponds to linear dimensions $50/h * 200/h$ pc^2 ($h = $ H/100 km/s $*$ Mpc) for NGC 4151.

The nucleus of the NGC 4151 was observed during individual periods in

Table 1 Log of NGC 4151 observations with the TV scanner.

Observation dates		*Number of spectra*	*Dispersion* (*Å/channel*)
1986 March	13–31	12	1
April	1–11	5	1
1987 March	5–10	2	2
April	6–30	4	1; 0.5
May	4–31	12	0.5 ÷ 2
1988 February	7–29	8	1
March	7–10	8	1
June	7	3	1
December	15	2	1
1989 July	6–7	3	1
December	19–30	8	1
1990 January	15–29	6	1
February	25–27	5	1
March	25–26	4	1

different years 1986–1990. The data of the observations are presented in Table 1. Most spectra were obtained with a dispersion of 1 Å/channel (≈60 Å/mm) at a 3–4 Å spectral resolution and a signal-to-noise ratio $S/N = 10$–25 for individual spectra. Exposure time was different and depended on the seeing conditions. Average integration time was a few tens of minutes. More details about observation procedure and processing are given by Bochkarev *et al.* (1989, 1991).

The spectral range from >3900 Å to 4950 Å was selected with a view to cover the maximum possible number of broad emission lines in the spectrum of the nucleus. The line [O III] λ4959 Å should be left outside the spectrum because this line could be integrated only under strong non-linear operation conditions of the scanner.

The initial processing was made using the standard procedure of flat field corrections and night sky subtraction, but without spectral sensitivity correction, because the main interest was to study the profiles of the He II broad component. Stellar component of NGC 4151 nucleus spectra was subtracted for $\lambda > 4200$ Å, using a high signal-to-noise ($S/N = 100$) spectra of nucleus of the standard elliptical galaxy NGC 4339 (Filippenko & Sargent 1988) by a procedure discussed in detail by Bochkarev *et al.* (1989). The spectra were divided by the continuum, that was drawn through the points marked visually on a the screen in such a way that they would approximately correspond to the center of the noise track. Spline approximation was made between the points.

After the initial processing, all the spectra were normalized to the intensity of the narrow component of the He II line. The sense of the procedure is that the counts for the He II central intensity measured from the broad component base, were correct, because the broad lines are formed in a region that is much smaller than the region where the narrow components are formed. Since the broad component of He II is weak (the relative intensity in the centre of the narrow component with respect to the broad component of He II ≈ 10) and is much broader than the narrow component, the errors arising from separation of the He II components do not seem to exceed a few per cent.

3. VARIABILITY OF ASYMMETRY OF THE BROAD COMPONENT OF THE LINE He II λ4686 Å

The spectra, that were obtained during 5 years make it possible to study the broad component of the He II line λ4686 Å, and other permitted lines, on timescales of a few years. Figures 1 and 2 present the spectra of NGC 4151 in 1986–1990. The spectra were averaged over 1 ÷ 2 months in those cases when sets of the observations of the nucleus of NGC 4151 were separated by less than 2.5 months.

Analysis of Figures 1, 2 shows that the broad component of the line He II λ4686 Å changed its asymmetry during 5 years. In 1986 the broad component of He II λ4686 Å had noticeable red asymmetry (the intensity of the red wing is more than that of the blue one). In 1987 the broad component of He II, and hydrogen lines, decreased by 65% as compared to 1986. To that moment, the broad component of the He II line was symmetrical.

In 1988 the intensity of the broad component of the hydrogen lines increased again almost up to its former value, but the broad component of the line He II λ4686 Å changed its asymmetry from the red (Mar–Apr 1986) to the blue one (Feb–Mar 1988). Subsequent observations (Apr and Dec 1988) showed a

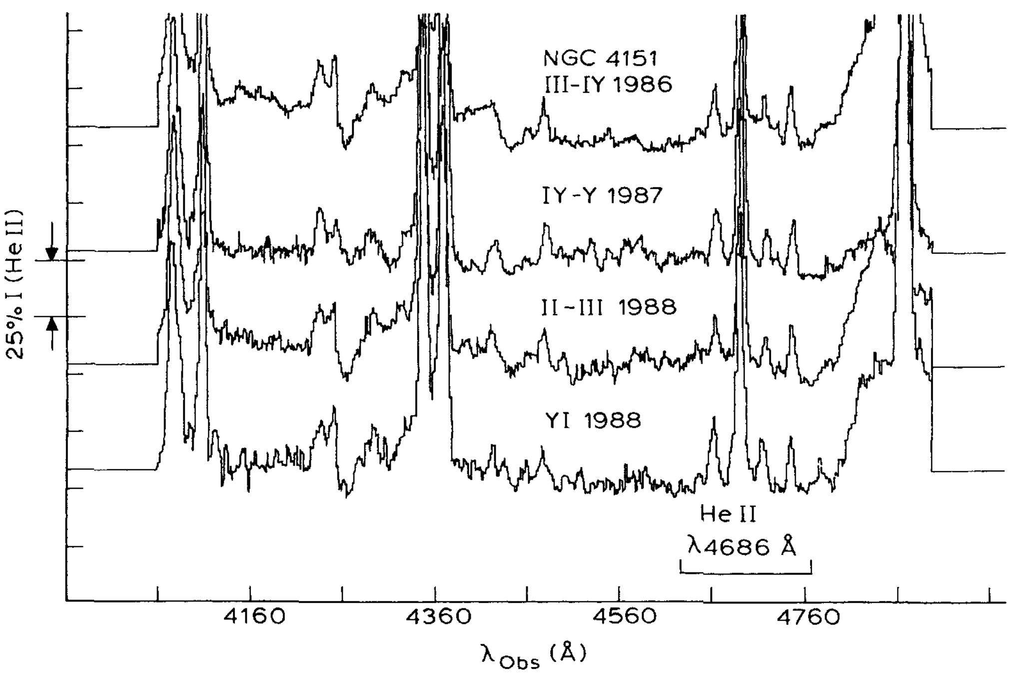

Figure 1 The average spectra of Mar–Apr 1986, Apr–May 1987, Feb–Mar 1988, and Jun 1988 of NGC 4151 after subtraction of the stellar component for λ > 4200 Å, divided by the continuum and normalized to the narrow component of the He II λ4686 Å line. Indicated as the abscissa is the observed wavelength in Angstroms. One degree of the ordinate axis is 25% of the intensity of the narrow component of the He II λ4686 Å line.

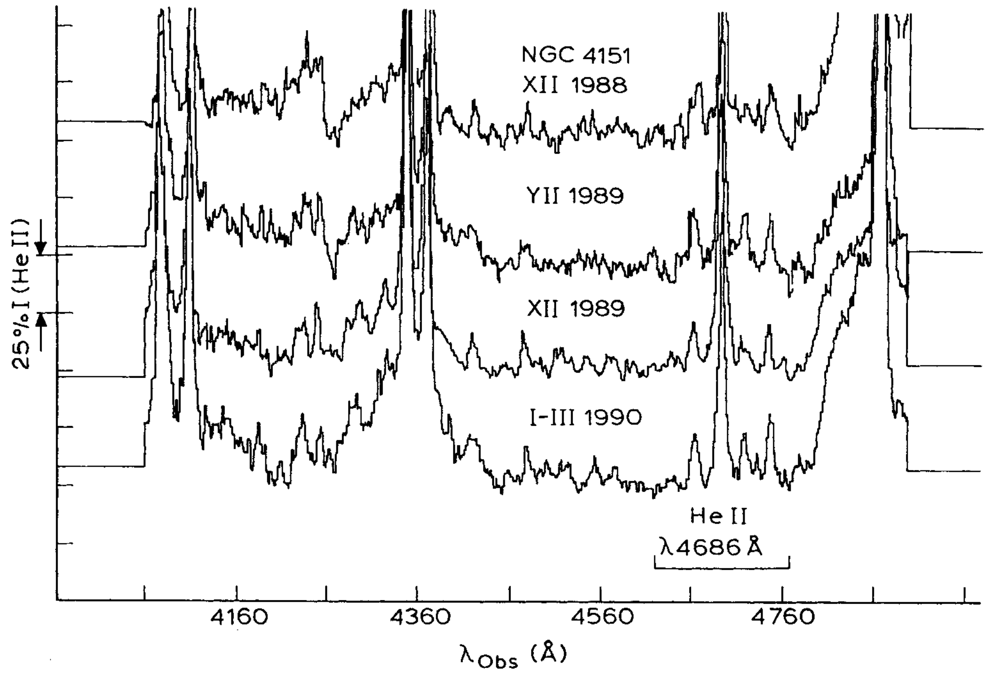

Figure 2 The same as on Figure 1 for Dec 1988, Jul 1989, Dec 1989 and Jan–Mar 1990.

decreasing asymmetry of broad component of He II λ4686 Å. In July 1989 a new decrease (but smaller than in 1987) of wings of hydrogen lines was observed, as well as presence of a weak asymmetric broad component of the He II line. A deeper minimum of hydrogen lines intensity has probably taken place in Jan–Mar 1989 but we have no data on that period of time. UBV photometry (Solomon *et al.* 1990) shows that during one month from the end of March to April 17, 1989 U-band flux decreased, approximately, by a factor of 1.4.

After a weak minimum of 1989, hydrogen line wings as well as the broad component of the He II λ4686 Å, increased again. During Jan–Mar 1990, asymmetry of the He II broad line became observable with the blue wing stronger than the red one, as in 1986. So, from 1986 to 1990, two minima of different depths (in 1987 and 1989) were observed. No changes of asymmetry of hydrogen lines as well as He I λ4471 Å have been seen during this time interval. But asymmetry of the He II λ4686 Å broad line has changed twice. Therefore, the characteristic time-scale of the He II broad component asymmetry changes is about two years, and recurrence to the initial sign of the line asymmetry has taken place during 4 years.

Figure 3 shows spectra near the He II line λ4686 Å, in a larger scale for dates when asymmetries of the He II broad component were pronounced. Comparison of the spectra by Mar–Apr 1986 and Jan–Mar 1990, when asymmetries of the He II line were similar, shows that hydrogen lines in the periods are different. According to Lyutyi's, Oknyansky and Chuvaev (1991), photometry, continuum intensity in Jan–Mar 1990 increased in comparison to Mar–Apr 1986 by about a

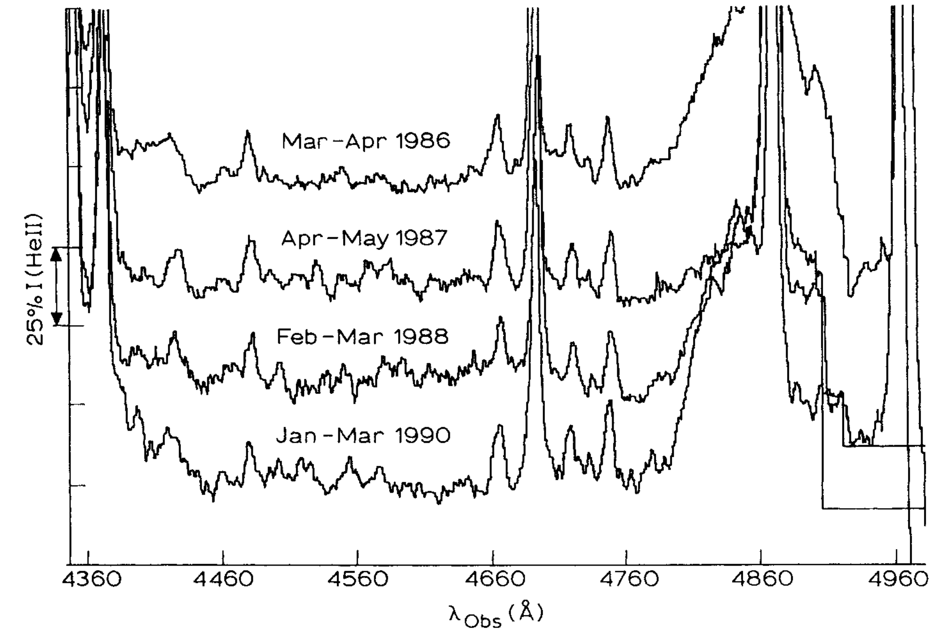

Figure 3 The same as on Figure 1 in a larger scale for the dates when asymmetries of the He II broad component were pronounced.

continuum is assumed to be a reason of a weaker asymmetry of the He II line in 1990 relative to 1986.

As can be seen on Figure 1 and 2, the spectra are similar for Apr–May 1987 and Jul 1989, when the hydrogen line broad components were the weakest, and asymmetry of the He II lines was not observed.

4. DISCUSSION

If we suppose that ≃4 years is the full cycle of changes of the He II line asymmetry, the natural questions are about the origin of the quasiperiodic variations and about possible independent evidences of the cycle. There are two observational evidences of similar periodicity in the NGC 4151 nucleus. At first, long term UBV observations (Lyutyi 1977; Gill *et al.* 1984) show two characteristic time-scales of variations, one of which is 3–5 years. Secondly, X-ray observations supply us with evidence of variations on the same time-scale (Yaqoob & Warwick 1989).

We can try to understand a reason for the changes of the He II line asymmetry from the point of view of the BLR model developed by Collin-Souffrin *et al.* (1982, 1988), Collin-Souffrin and Dumond (1986, 1989), and Netzer (1987). According to the model, BLR consists of two zones mentioned in section 1:

1. High ionization line region (HIL or H II zone) above the accretion disk (near jets) with column density $N = 10^{22}$–$10^{23}\,\mathrm{cm}^{-2}$, and electron number density $n_e = 10^5$–$10^{10}\,\mathrm{cm}^{-3}$, where emission in lines of C IV, C III]. Lα, N V, He II is formed.

2. Low ionization line region (LIL or H I zone) located on the periphery of the accretion disk. The LIL regions are characterized by $N \leqslant 10^{25}\,\text{cm}^{-2}$ and $n_e \simeq 10^{12}$–$10^{13}\,\text{cm}^{-3}$ and emit Fe II, Mg II, C II, and other lines, as well as Balmer lines and the Balmer continuum.

We can try to interpret the time-scale of ≃2 years for the He II λ4686 Å broad component asymmetry changes discussed above (see Fig. 1, 2), as a reaction of HIL region on variations of far UV–X-ray ionizing radiation. If the accretion disk axis has an inclination angle i, delay time in the red wing relatively to the blue one is approximately $\tau = 2\text{R}\cos i/c$, where R is the distance from the galactic center to the region of the He II λ4686 Å broad line formation.

If changes of the line asymmetry are interpreted as a result of delay of variations in the red wing relatively to the blue one (for movement of gas from a center), 2 years lagging time corresponds to the distances of the line emission $R \geqslant 10^{18}$ cm. Taking into account that value of the column density of HIL zone during the years of minimal nucleus brightness is equal to $N \simeq 5 * 10^{22}\,\text{cm}^{-2}$ (Yaqoob & Warwick 1989), number density of the gas in the case of its homogeneous distribution $n_e \leqslant 5 * 10^4\,\text{cm}^{-3}$.

For estimation of a size of the emission region for such gas in the He II λ4686 Å line, we have calculated photoionization models. Taking into account uncertainties of the far UV spectrum of NGC 4151, we have made calculations with various slopes of power-law ionizing spectra $\alpha = 0 \div 2$ for different number densities of gas $n \leqslant 10^5\,\text{cm}^{-3}$. We suggest that the gas is optically thin and has normal abundances according to Stasinka (1990). We solved a system of equations of radiative transfer for initial and diffuse ionizing radiation equations, of ionization equilibrium for H, He, C, N, O, Ne, Mg, Si, S, Ar, statistical equilibrium for metastable levels ions of heavy elements, and thermal equilibrium. For ionization equalibrium we take into account radiative and dielectic recombinations and charge transfer reactions as well as photoionizations by initial and secondary (diffuse) ionizing radiation. Heating by initial and secondary radiation and cooling in the result of electron excitation, electron ionization, radiative and dielectronic recombinations, free-free emission were considered for thermal equalibrium.

Table 2 represents results for helium: on the distance less, or about, 0.3 pc, He III is the most abundant. Therefore, strong emission in He II lines is produced by means of recombinations, He II λ4686 Å line luminosity is:

$$L(4686\,\text{Å}) = n(\text{He III})n_e\alpha_{\text{eff}}(4686\,\text{Å})\text{V}h\nu \simeq 2 * 10^{39}\,\text{erg/s},$$

where n(He III) and n_e are number densities of He III ions and electrons (in our case $n_e \simeq 1.1\,n$, where n is the number density of heavy particles, mainly H and He). V, volume, α_{eff} (4686 Å), is an effective coefficient of recombination resulting in radiation of a He II λ4686 Å photon, $h\nu$ is the energy of the photons. Observed luminosity of the broad component of the He II λ4686 Å line of NGC 4151 $L(4686) \simeq (2\text{–}3)/10^{39}$ erg/s (for the distance of 10 Mpc for the Hubble constant H = 100 km/s * Mpc, Schiltz 1987) follows from observations of Boksenberg & Shortridge (1975), Penston & Perez (1984). Recombination time for the gas $t_r = (\alpha n_e)^{-1} \simeq 10^7$–$10^8$ s is approximately the same as the time delay.

In expression for $L(4686)$ we suggest that the radiating volume V has a form of two cones with semiangles ≃60° and altitudes $10^{18}\,\text{cm} \simeq 0.3$ pc. Using such geometry gives a chance to understand the ≃2 yr time-scale for changes of the

Table 2 Ionization state of He in low density gas irradiated by a central source of power-law spectrum with the slope α.

α	*R, pc*	*N*, cm^{-3}	*N(He II)*, cm^{-3}	*N(He III)*, cm^{-3}	$T_e * 10^{-3}$, *K*
0	0.1	10^4	2.4 E − 3	9.1 E + 2	129
		10^5	2.6 E − 1	9.1 E + 3	100
	0.5	10^4	3.4 E − 2	9.1 E + 2	100
		10^5	3.4 E − 0	9.1 E + 3	100
1	0.1	10^4	1.8 E − 2	9.1 E + 2	85
		10^5	2.1 E + 0	9.1 E + 3	65
	0.5	10^4	4.1 E − 1	9.1 E + 2	52
		10^5	4.3 E + 2	6.7 E − 2	11
2	0.1	10^4	1.1 E − 1	9.1 E + 2	71
		10^5	9.1 E + 3	7.9 E + 0	10
	0.5	10^4	4.2 E + 1	8.7 E + 2	29

He II λ4686 Å line asymmetry by delay of radiation from one cone (forming blue part of the line) relatively to the other one.

Thus, the above-mentioned assumption is self-consistent. Nevertheless, the suggested size for the He II broad component, strongly contradicts the lagging variation in the He II line relatively to the continuum, which is $\tau = 6 \pm 4$ d for NGC 4151 (Peterson & Cota, 1988). Moreover, the response of the core of the C IV λ1549 Å line to the continuum variation is delayed by $3.2 \pm 3\,d$ with respect to the response of its wings. But He II and C IV have approximately the same ionization potentials and are probably formed in one place. Therefore, it is problematic to connect the 2 yr delay in the variations of the blue and red wings of the He II λ4686 Å line by a gas located on 10^{18} cm from the nucleus. It probably means that there are two different areas of the broad He II line formation; inner with $r \simeq 10^{16}$ cm, and outer with $r \simeq 10^{18}$ cm. The last one can be approximately the same as for the Fe X λ6374 Å line.

The other possible reason of variation of the H II line assymetry, is the variation of geometry of gas emitting He II lines on a time scale $t_w = 2$ yr in a volume with size $c\tau = 1.5 * 10^{16}$ cm. In this case the speed of geometry changes is only $c\tau/t\omega \simeq 300$ km/s, which is comparable with gas velocity in the volume. It can probably be the variation in formation of clouds with different velocities or a precession-type movement in a ring of the accretion disk, which radiates the He II λ4686 Å line.

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