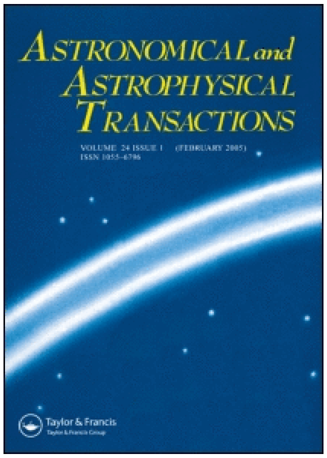

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BROAD EMISSION LINES Lα, C IV AND Hβ IN NGC 5548

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The ultraviolet and optical spectra of the active galaxy NGC 5548 were taken from the active galactic nuclei watch database in the 1993 monitoring campaign. The ratios of the line intensities of C IV to Lα and at Lα to Hβ have been measured at different parts of the line profiles. Both ratios are at all times high in the low-velocity centre(s) of the lines but decrease in the high-velocity wings. Theoretical modelling of the two C IV-to-Lα and Lα-to-Hβ ratios using the standard photoionization code CLOUDY show that the observed line ratios can be accounted for by a system of clouds illuminated by the central source and located at different distances from the centre. The possible geometry of NGC 5548 is discussed.

Keywords: Seyfert galaxies; Emission line profiles; NGC 5548

1 INTRODUCTION

High temporal frequency monitoring of Seyfert galaxies (active galactic nuclei) (AGN) watch programme over an extended period has proved to be a powerful way to understand the structure and the physical conditions of the broad-line region (BLR). In a previous paper by the present author and co-workers (Dumont et al., 1998) we have discussed some results of the AGN watch programme concerning the BLR of the Seyfert 1 galaxy NGC 5548 and, on the basis of photoionization modelling, we have demonstrated that there are three problems: an energy budget problem, a line ratio problem and a line variation problem. We have discussed several possibilities of uncertainties in our analysis such as the reddening, the overall spectral distribution, the influence of optically thin clouds and the possibility of a special geometry of the BLR. We concluded that none of these could help to solve all three problems at the same time. We were led to propose that a large fraction of low-ionization lines (LILs) such as the Balmer lines is emitted in a region which has only very weak variations or no variations at all. One possible hypothesis is that the constant fraction of emission comes from regions which are non-radiatively heated. Kaspi and Netzer (1999), who also found that the light curves of the Balmer lines and possibly of the Mg II line do not fit the general pattern of the other lines, invoked the limitation of present-day photoionization codes, owing to the use of the escape probability formalism.

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A clue to the problem can lie in a detailed study of the physical conditions along the line profiles together with line profile variations, since it provides insight into the distance between the black hole and the emission region, if different parts of the line profiles are produced at different distances from the centre. For this purpose we have examined the variability along the line profiles of the Lα, C IV and Hβ lines for approximately 1 month, using available results of simultaneous ultraviolet (UV) and optical observations in 1993 obtained during extensive monitoring in the framework of the AGN watch programme.

The paper is organized as follows. The observational data, taken from the AGN watch database is described in Section 2; the analysis of the profile variability of the Lα, C IV and Hβ lines in NGC 5548 is performed in Section 3 and the theoretical modelling of the emission line intensities and line ratios is given together with the discussion in Section 4.

2 OBSERVATIONAL DATA ON NGC 5548

UV and optical spectra of NGC 5548 were obtained from the AGN watch database for 1993. We have chosen four spectra in the UV and four spectra in the optical bands, all at about the times of the minimum and of the maximum luminosity. Table I presents the information concerning these spectra.

Figure 1(a) shows the continuum light curve at $\lambda = 1350$ Å and Figure 1(b) the spectral energy distribution of the central source of NGC 5548 taken from the previous paper by the present author and co-workers (Dumont et al., 1998) and the canonical AGN continuum from the work of Mathews and Ferland (1987). The arrows in Figure 1(a) indicate the Julian dates (JDs) of the minimum activity and of the maximum activity, selected for this study. According to the AGN watch campaign the time lag between LILs such as the Balmer lines varies from 13 to 20 days (Peterson et al., 1999). The time lag between the continuum and the Hβ line flux obtained from ground-based monitoring during 1993 is 13.61 ± 1.6 days (Peterson et al., 1999).

The time lag of high-ionization lines (HILs) varies probably from 1 year to a time lag like that of hydrogen lines. The lags for the Lα and C IV lines correspond to a distance from the central source of approximately a half of that for the Hβ line (Peterson et al., 1991, 1992, 1994; Korista et al., 1995). Therefore in both states of activity, we choose spectra of the Hβ, C IV and Lα lines taken 13 and 6 days respectively after the dates indicated in Figure 1. Let us call the period from JD 2449098 to JD 2449107 'a minimum' and the period from JD 2449128 to JD 2449135 'a maximum' of nuclear activity.

TABLE I Log of Spectroscopic Observations.

File name	Date	Julian date	Line
n549099.lis	April 21, 1993	2448998.97	Lα, CIV
n549107.lis	April 29, 1993	2449106.94	Lα, CIV
n549128.lis	May 20, 1993	2449127.90	Lα, CIV
n549135.lis	May 28, 1993	2449135.06	Lα, CIV
n59099a.dat	April 22, 1993	2449099.80	Hβ
n59107a.dat	April 30, 1993	2449107.82	Hβ
n59128a.dat	May 21, 1993	2449128.73	Hβ
n59135a.dat	May 28, 1993	2449135.76	Hβ

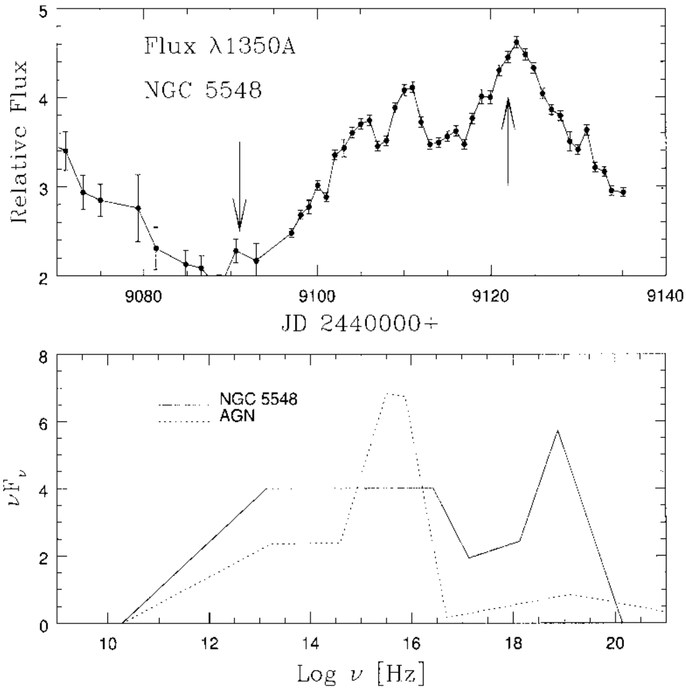

FIGURE 1 (a) The continuum light curve at $\lambda = 1350$ Å. Arrows indicate the maximum and the minimum states of activity. (b) The spectral energy distribution in NGC 5548, together with the canonical AGN continuum from the work of Mathews and Ferland (1987). Continua are plotted in νF_ν with arbitrary offsets.

3 ANALYSIS OF THE LINE PROFILES

The profiles of the C IV, Lα and Hβ lines have been divided into seven parts, the width of each part being equal to $2000\,\mathrm{km\,s^{-1}}$. The core of the lines is measured between -1000 and $+1000\,\mathrm{km\,s^{-1}}$. Thus, the blue and red wings have widths of $\pm 700\,\mathrm{km\,s^{-1}}$.

Figure 2 shows that the structures of the red side in the Lα and C IV lines are nearly similar at both stages of nuclear activity. The profile shape of the Hβ line differs from the HILs Lα and C IV but has a small shoulder which is stronger at the maximum (right-hand side). Wanders and Peterson (1996) identified three components in the Hβ line, which change their relative intensity over the years but not their position in the line profile. These components vary independently of one another: a relatively narrow central component and somewhat broader red- and blue-wing shoulders at approximately $\pm 2500\,\mathrm{km\,s^{-1}}$.

The difference between the line fluxes, $\log \Delta F = \log (F_{max} - F_{min})$, along the line profiles plotted with arbitrary offsets is shown in Figure 3. The Lα, C IV and Hβ variations exhibit two clear components: one to the left and one to the right of the line centre. However, the difference ΔF between the line fluxes for Lα and C IV is significantly larger than for Hβ. This effect, known as 'the line variations problem', has been discussed by Dumont et al. (1998). They found that the variations in the LILs (such as Hβ) are smaller than could be expected from the variations in the continuum at $\lambda = 1350$ Å although HILs (such as Lα and C IV) do not have a similar problem. Analysis of the C IV-to-Lα and Lα-to-Hβ line ratios along the profile of the lines (Fig. 4) shows that these ratios are high in the centre of lines and decrease towards the wings for both states of nuclear activity. A similar analysis for the difference ΔF between the line fluxes along the line profiles presented in Figure 5

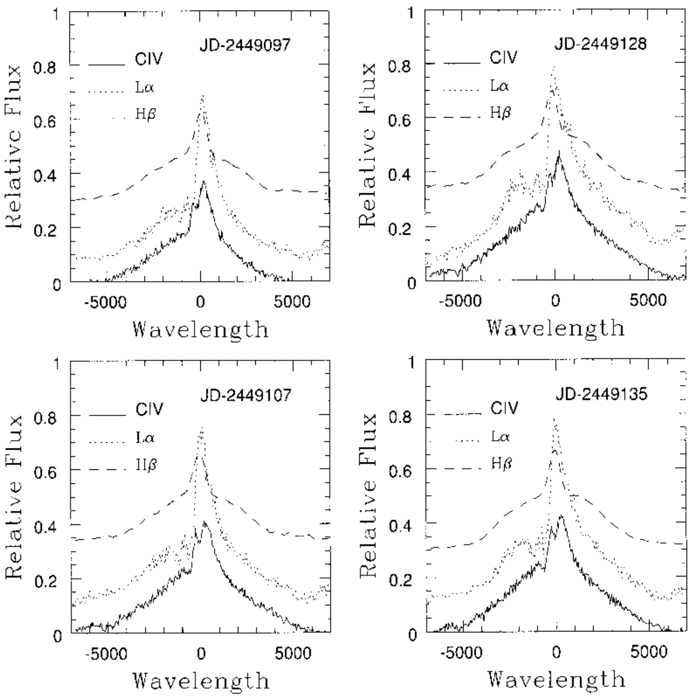

FIGURE 2 The line profiles (a), (c) at the minimum and (b), (d) at the maximum states of activity.

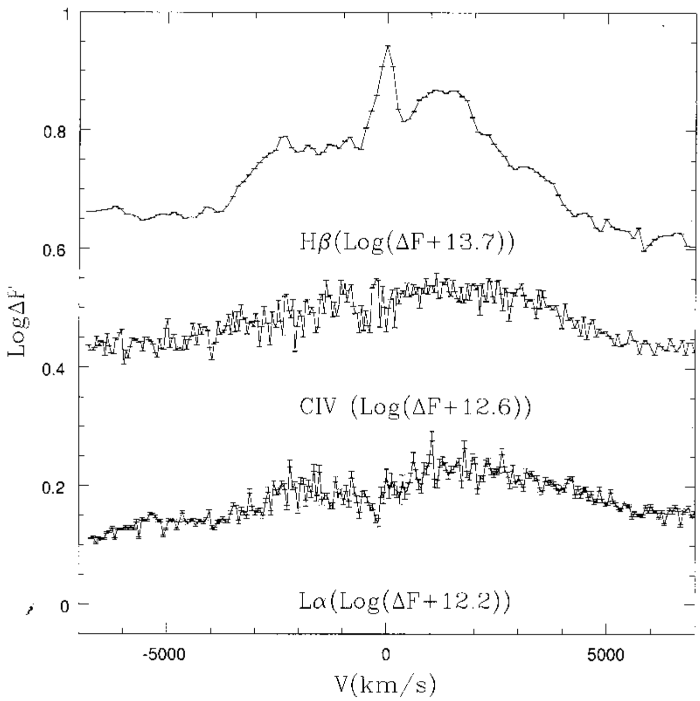

FIGURE 3 The difference between the line fluxes, $\log \Delta F = \log (F_{max} - F_{min})$, along the line profiles plotted with arbitrary offsets.

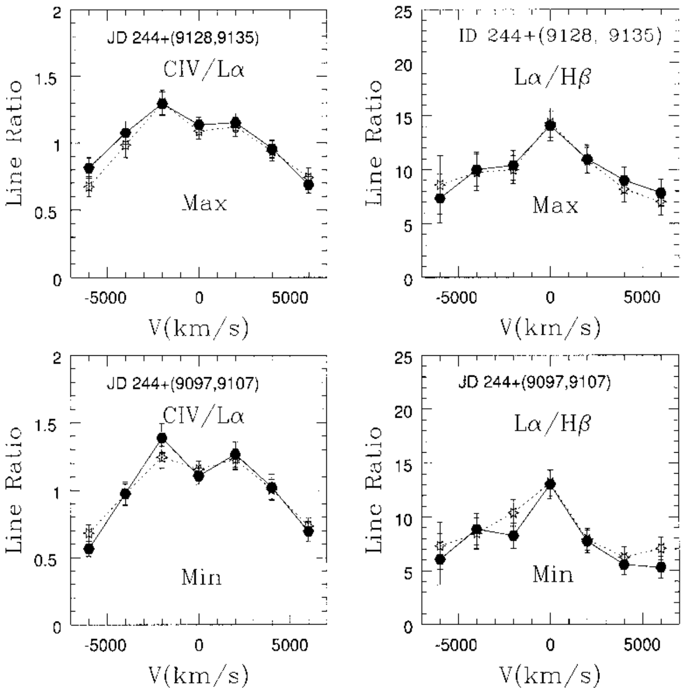

FIGURE 4 The C IV-to-Lα and Lα-to-Hβ line ratios (a), (c) for the minimum and (b), (d) for the maximum states of nuclear activity.

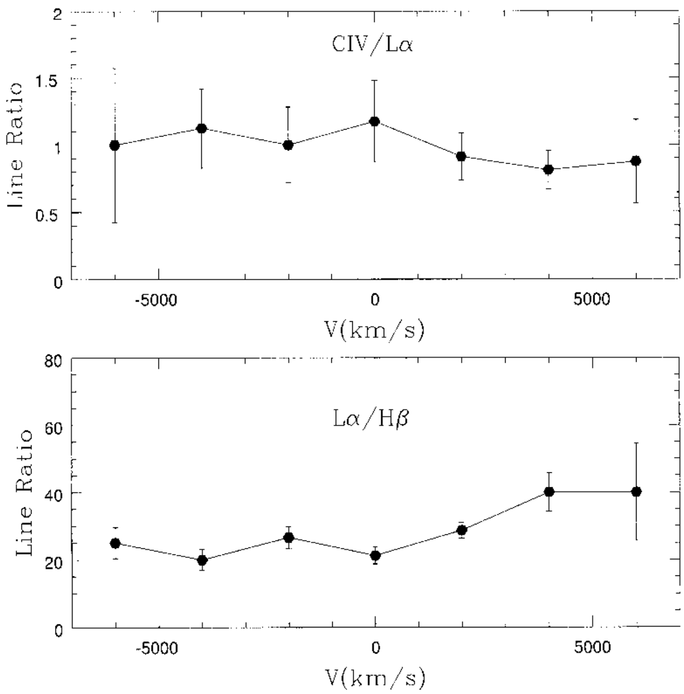

FIGURE 5 (a) The C IV-to-Lα and (b) the Lα-to-Hβ line ratios for the difference ΔF between the line fluxes along the line profiles.

shows the nearly similar ratios of the C IV-to-Lα and Lα-to-Hβ line ratios along the line profiles.

4 THE PHOTOIONIZATION MODELS

The modelling of the observed C IV-to-Lα and Lα-to-Hβ line ratios has been carried out with the photoionization code CLOUDY, version c9005 (Ferland, 1998), in its plane-parallel version, and assuming solar abundances. The assumed spectral distribution of the central continuum is the same as in a previous paper by the present author and co-workers (Dumont et al., 1998). Figure 1(b) displays this continuum together with the canonical AGN continuum given by Mathews and Ferland (1987). Adopting an observed mean flux of 5×10^{-11} erg cm^{-2} s^{-1}, we can estimate the flux from the central source illuminating the clouds.

The time lag between the continuum variations and that of the Balmer lines varies from 13 to 20 days (Peterson et al., 1999). The lag of Lα and C IV lines is approximately twice that for Balmer lines (Korista et al., 1995). The computations have been made with the surface fluxes $\log(\nu F_\nu) = 10$, 9.5, 9, 8.5 and 8 erg cm^{-2} s^{-1} at 0.1 Ryd. These fluxes illuminate 1 cm^2 of the clouds located at approximate distances of 6, 10, 18, 33 and 58 light days. The electron density varies from 10^8 to 10^{13} cm^{-3}. The computations are made for an electron density varying from 10^8 to 10^{13} cm^{-3}. We stop the computation at the column density N_h given by $\log N_h = 25$ cm^{-2}. Figure 6 shows the intensities of three lines versus

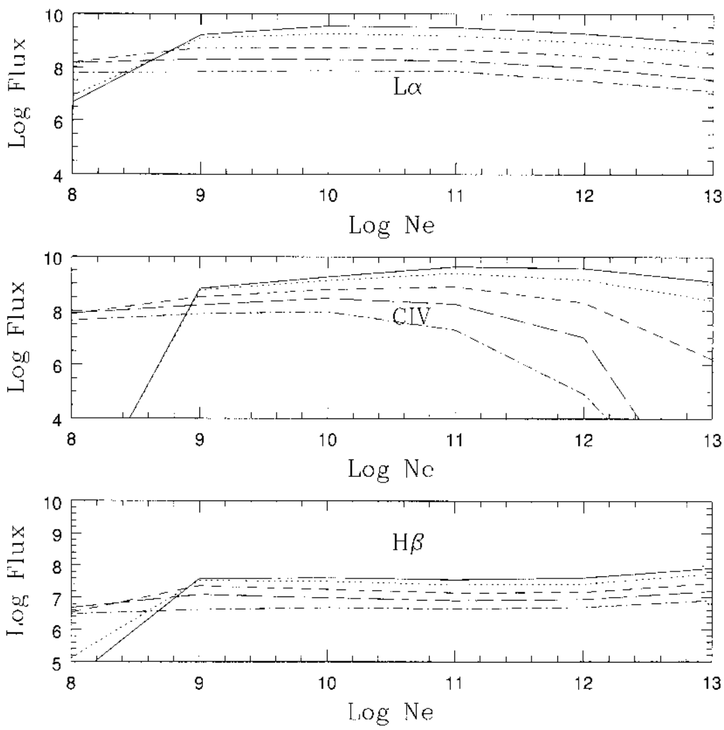

FIGURE 6 The (a) Lα, (b) C IV and (c) Hβ line intensities versus the electron density at the following distances from the central source: ——, 6 light days; · · · ·, 10 light days; - - - -, 18 light days; — —, 33 light days; — · —, 58 light days.

the electron densities at different distances from the central source. The intensity of the C IV line decreases with increasing electron density above $N_e = 10^{10}\,cm^{-3}$ significantly faster than that for Lα but the Hβ line stay nearly constant.

From the comparison of the observed and computed C IV-to-Lα ratios of about 0.5–1.4 (Fig. 7), we can see that the electron densities along the lines (from the wings to the centre) may change from 10^9 to $10^{11}\,cm^{-3}$ for most distances from the centre. However, for electron densities of 10^{10}–$10^{13}\,cm^{-3}$ this is only true for the regions located at the distances 18 light days or more from the centre which do not correspond to the observed lag for the C IV and Lα lines.

The observed Lα-to-Hβ ratio of about 5–15 is small compared with that from the computed models except at extremely high electron densities and at distances from the centre further than predicted from the Hβ lag. Thus, there is a contradiction between the electron densities obtained from both ratios. We accept that the electron density obtained from the C IV-to-Lα HIL ratio corresponds to the HIL zone with the electron densities $N_e \approx 10^9$–$10^{11}\,cm^{-3}$ while the LIL zone is located further than predicted from the lag and has the electron density $N_e \approx 10^{12}$–$10^{13}\,cm^{-3}$. It is interesting to note that the observed line ratios of the variable part of the lines, a C IV-to-Lα line ratio of about 1 and an Lα-to-Hβ line ratio of about 20–40 (Fig. 5) corresponds to the emission from the gas with electron densities of 10^9–$10^{11}\,cm^{-3}$. It needs to be stressed that the distance of the vaiable part of the Lα, C IV and Hβ lines from the centre is less than 18 light days. Thus, we may say that the variable part of the lines is emitted from the HIL zone.

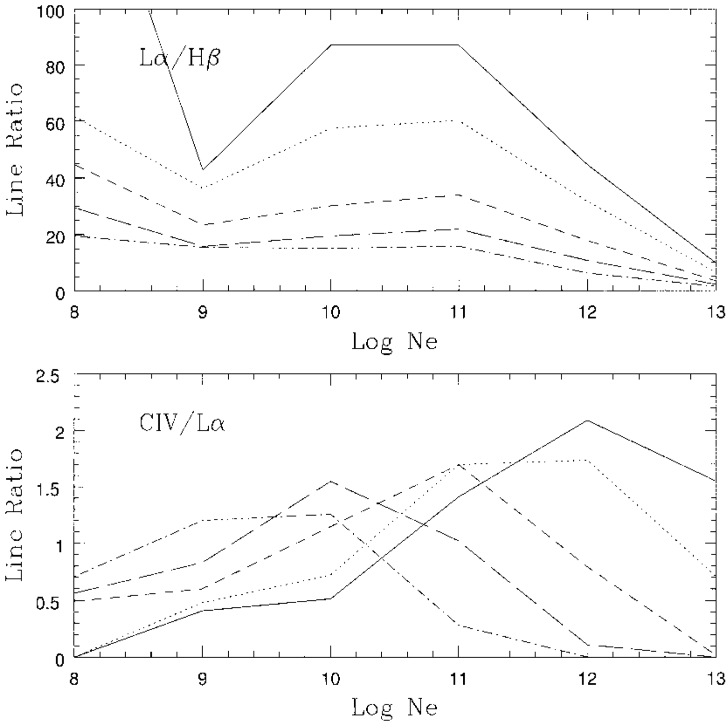

FIGURE 7 (a) The C IV-to-Lα and (b) the Lα-to-Hβ theoretical line ratios versus the electron density. Surface fluxes correspond to the flux of the central source at distances of 6 light days (——), 10 light days (. . . . . .), 18 light days (- - - -), 33 light days (—–—), and 58 light days (— · —).

An analysis of the difference line fluxes at the minimum and at the maximum shows that the observed variable parts of the Lα and C IV lines is 28% of the total intensity of these lines at the maximum. However, the variable part of the Hβ line is only 10% of the total intensity of Hβ at the maximum. Moreover the observed variable part of lines along the line profiles (Fig. 3) shows two components for the lines although the intensities of the variable parts are different. The double structure of the variable parts of the lines needs to be studied more in different active galaxies before we may say whether its structure is due to the emission from an accretion disc or from the regions above an accretion disc. According to the results of this study we suggest that the variable part of the lines corresponds to the HIL zone and forms above an accretion disc. A significant non-variable part of the LIL zone is emitted from an accretion disc. In this case the lag obtained for the variable part of Hβ may not correspond to the true distance of the LIL zone from the centre.

In a previous paper (Dumont et al., 1998) we have demonstrated that there are three problems: an energy budget problem, a line ratio problem and a line variation problem. Let us consider these based on a new two-component model of NGC 5548.

(i) The energy budget problem. Let us consider the luminosity of the Hβ line first. The observed flux of Hβ at the maximum (JD 2449127.9) is 1.5×10^{-12} erg cm^{-2} s^{-1}. If the variable part includes 10% of the total intensity of this line, then the non-variable part is 1.35×10^{-12} erg cm^{-2} s^{-1} which corresponds to the luminosity 6.3×10^{41} erg s^{-1}. The coverage factor should be smaller than 1/2 (which means emission from one side of the cloud), since it is difficult to imagine a geometry where the whole BLR is located on the same side of the illuminating source. Let the coverage factor be 0.5 or less. In this case the surface flux at a distance of about 33 light days should be 1.36×10^{7} erg cm^{-2} s^{-1} or greater. The calculations show that the surface flux in Hβ is 8.7×10^{6} erg cm^{-2} s^{-1} for $N_e = 10^{12}$ cm^{-3} and 2.1×10^{7} erg cm^{-2} s^{-1} for $N_e = 10^{13}$ cm^{-3}. However, the surface flux of Hβ required at a distance of about 58 light days equals 5.5×10^{6} erg cm^{-2} s^{-1} ($N_e = 10^{13}$ cm^{-3}). This is less than half that predicted by computations. Thus, the remote photoionized region (located at a distance of 33 light days or more from the centre) may solve the energy budget problem in the Hβ line.

(ii) The line variation problem. Small variations in the LILs (such as Hβ) compare with those of the HILs (such as Lα) because a large fraction of LILs are emitted from a remote region. The contribution from the remote regions at a distance of 33 light days or more from the central source to the emission in Hβ is 90% and at a distance of about 35 light days is 10% in Lα.

(iii) The line ratio problem. Figure 5 (Dumont et al., 1998) shows that the theoretical ratios of lines close to the observed ratios are predicted by the emission from remote regions (33 light days or more). Since the line ratios change significantly along the line profiles the contributions from LILs and HILs should be taken into account. Let us consider the ratios discussed in this paper. Small Lα-to-Hβ ratio observed in the wings of lines could be due to the emission from the dense remote regions of an accretion disc. However, the central part of the lines is emitted from the HIL where this ratio is large. The C IV-to-Lα ratio decreases in the wings and could be due to the contribution to the emission in the Lα line from the remote LIL regions. The C IV line is emitted mainly from the HIL regions near to the nucleus.

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