The peculiar Balmer line profiles of OQ 208

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\textbf{Running Title:} Balmer Line Profiles of OQ 208

\textsuperscript{1} Based in part on observations collected at ESO, La Silla
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Abstract

We present spectrophotometric observations of the Broad Line Radio Galaxy OQ 208 (≡ Mrk 668 ≡ 14040+286) obtained between 1985 and 1991. We show that the Balmer line fluxes and profile shapes undergo remarkable changes. The ratio of intensities between the broad and narrow components of Hβ increased monotonically from ∼ 15 in 1985 to ∼ 40 in 1991. The peak of the broad components of Hβ and Hα were known to be strongly displaced to the red. We have discovered a correlation between the amplitude of the broad peak displacement and the luminosity of Hβ, in the sense that the displacement is larger when the line luminosity is higher. The line profiles and the correlation are analyzed in light of several competing models for the Broad Line Region (BLR). We conclude that the observations are not compatible with either a binary BLR model or one involving ballistic acceleration of the line emitting gas.

Radiative acceleration of a system of outflowing clouds readily explains the correlation between line shift and luminosity as well as the peculiar line profiles. Self-absorption in the Balmer lines or dust absorption in the non illuminated face of the clouds is necessary to explain the asymmetry associated with the red peak. Thus it seems that most or all of the Balmer emission originates from the inward face of the clouds. Theoretical line profiles computed for clouds accelerated by radiation pressure in various geometrical configurations suggest that the observed Hβ profile is best fit assuming the contribution of an ensemble which might be spherical or confined in a thick disk in addition to a component emitted in a thin shell contained in a cone of half opening angle ∼ 12° seen along its axis. Another composite model for the BLR, in which the line is emitted partly by (1) a relativistic disk seen nearly pole on and (2) infalling matter is not favored – but not excluded – on the basis of the present data.

Subject Headings: Galaxies: active – Galaxies: individual (OQ 208≡ 14040+286) – Galaxies: kinematics and dynamics – Galaxies: Seyfert – Line: profiles
1 Introduction

Balmer line profiles in AGN are presumed to reflect geometric structure and kinematics in the broad line region (BLR). These profiles show a confusing array of both red and blue shifts as well as asymmetries (Sulentic 1989). The importance of the objects showing peculiar profiles has received increasing recognition in the past few years. It is thought that these objects can offer a unique insight into the structure of the BLR. Objects with the largest line shifts or asymmetries might represent, for instance, preferred source orientations to our line of sight. Very regular profiles (often with logarithmic shape) can be successfully modelled employing a variety of velocity fields (see Mathews & Capriotti 1986 for a review). Unfortunately this “degeneracy” prevents us from obtaining unambiguous evidence about the kinematics and geometry of the BLR. It is, for example, unclear whether the predominant motion in the BLR is rotational or radial and, if radial, whether it is predominantly in– or out–wardly directed. The broadest and/or most irregular line profiles in Seyfert and Broad Line Radio Galaxies (BLRG) might, on the contrary, provide a direct link to the structure of the BLR (see e.g., Penston, 1991; Robinson, Perez & Binette 1990). This is especially true if the profile shape is variable.

Rotation has been proposed as the dominant broadening mechanism for very broad or peculiar (sometimes “double peaked”) Balmer line profiles (Wills & Wills, 1986; Wills & Browne, 1986). Some profiles have been fitted using models for a relativistic accretion disk (e.g., Arp 102B: Chen, Halpern & Filippenko, 1989; Chen & Halpern, 1989; 3C332, Halpern, 1990: 3C 390.3, Perez et al. 1988). Nevertheless, simple disk models are not able to reproduce the majority of the observed line shifts and asymmetries in regular profiles (Sulentic et al. 1990), and the shape of peculiar profiles like those of Akn 120, IC 4329A and others (Marziani, Calvani, & Sulentic 1992). Refinements of the models (including for instance hot spots, as in the case of 3C390.3; Veilleux & Zheng, 1991) can reduce the disagreement between the expectation for disk emission and the observed profiles. Much theoretical work in this
direction remains to be done.

Spectroscopic data is being collected with growing attention devoted to peculiar objects but, with the possible exception of Arp 102B, the debate over the structure of the BLR is still open to many competing alternatives. The line profile peculiarities have been interpreted within the context of several models besides the accretion disk scenario including: a) binary black holes (Gaskell, 1983b), b) transient light-echoes (e.g., Penston 1991 and references therein) and c) a system of clouds in bipolar outflow (Zheng, Binette & Sulentic, 1990; Zheng, Veilleux & Grandi, 1991). Furthermore it has been pointed out (Marziani, et al. 1992) that it is not necessary to invoke ad hoc exotic mechanisms to explain the peculiarities of the profiles, since particular geometrical and/or viewing conditions may account for them. This can also be true under the assumption that the velocity field is basically the same in objects with irregular and regular line profiles.

OQ 208 (≡ Mrk 668 ≡ 1404+28) attracted our attention because its optical spectrum shows one of the largest peak displacements yet observed. It also shows some features more typical of Seyfert 1 or BLRG (Blake et al. 1970; Burbidge & Strittmatter 1972). This object has been classified as a BLRG because it exhibits rather strong radio emission from a central compact source. Osterbrock & Cohen (1979, hereafter OC79) made the first detailed study of the optical spectrum and discovered notable peculiarities in the broad Balmer line profiles. They pointed out that the peaks of the broad Hα and Hβ profiles were strongly redshifted (by about 2600 km/s) with respect to the narrow components of the same lines.

OC79 suggested that a combination of radial motion and obscuration, or self absorption, could account for the observed profiles. Although OQ 208 has been extensively monitored at radio wavelengths, even on a daily basis since it is a candidate flux calibrator (Waltman et al. 1991, and references therein), little attention has been paid to its optical spectrum in the past 15 years. Gaskell (1983a) showed an Hβ profile obtained in 1982, and interpreted it within the context of a binary black hole model. OQ208 is unresolved at VLA resolutions but the
radio core has been mapped recently using VLBI. Two components have been revealed at 8.4 GHz which are separated by \(\sim 1.3\) mas. Position angle changes from the highest to the lowest observed frequency suggest that the components could be the signature of a highly curved jet observed at different resolutions (Charlot 1990).

In this paper we present spectrophotometric observations of OQ 208 in the time period between March 1985 and February 1991. In § 2 we describe the observations and reduction procedures. The results on fluxes and line profiles are presented in § 3. We find that the H\(\beta\) flux varied strongly over the period of observation. The peculiar profiles of the Balmer lines are variable, and their variations allow us to place some unambiguous constraints on the BLR structure. In § 4 we restrict the choices of possible models able to explain the observed properties of OQ 208 in a simple way. We discuss the advantages and the difficulties of models involving line emission from: a) a binary BLR, b) an accretion disk c) an infalling component or a hot spot (§ 5), and d) outflow in the BLR (§ 6). We suggest – also on the basis of the model profile presented in § 6.2 – that the most plausible scenario to explain the Balmer line emission involves a system of clouds accelerated by radiation pressure in a biconical configuration plus an additional contribution from a cloud component that is either spherically symmetric or confined within a thick cylinder. In § 7 we describe additional observations that could test the model proposed here.

## 2 Observations and Data Reduction

### 2.1 Observations

Spectrophotometric observations of OQ 208 were carried out during the period 1985 to 1989 with the 2.5 m Isaac Newton Telescope (INT) at La Palma. The telescope was equipped with an intermediate dispersion spectrograph and an IPCS detector. The spectra were collected with a slit width of \(\approx 1.5\) arcsec. An additional, short exposure with a slit width of 5.0 arcsec was obtained after each exposure in order to ensure an accurate spectrophotometric
calibration. The slit was oriented at parallactic position angles to minimize wavelength
dependent losses. The use of a 300 l/mm grating yielded a dispersion of \( \approx 2 \text{ Å/pixel} \).

An additional spectrum of OQ 208 was obtained in April 1990 with the 1.52 m telescope
at the European Southern Observatory on La Silla. The telescope was equipped with a Boller
& Chivens spectrograph and an RCA high resolution CCD detector (pixel size 15\( \mu \text{m} \times 15\mu \text{m} \)).
The slit width was \( \approx 2.0 \text{ arcsec} \) at the focal plane of the telescope. The seeing was estimated
to be \( \lesssim 1 \text{ arcsec} \) during the observation. A 1200 l/mm grating allowed a dispersion of 60
Å/mm. OQ 208 was also observed at Kitt Peak National Observatory during February 1991
with the Gold Camera attached to the Cassegrain focus of the 2.1 m telescope. An 800 \( \times \) 800
pixel TI chip and a 600 l/mm grating were used yielding a dispersion of 1.3 Å/pixel. The slit
width was 2.5 arcsec and the angular scale at the focal plane of the spectrograph was \( \sim 0.8 
\text{ arcsec/pixel} \). The seeing was estimated to be 1.5 arcsec. The Journal of Observations given in
Table 1 lists the date when each spectrum was obtained along with the exposure time,
spectral dispersion and the wavelength range covered.

### 2.2 Data Reduction and Preliminary Analysis

A detailed report of the data reduction procedure for the spectra taken at the INT is given in
Perez (1987), while for the spectrum taken at ESO, detailed information can be found in
Marziani (1991) and Marziani, et al. (1992). Only the basic steps of the reduction procedure
are reported here.

The bias level was subtracted from all spectra, which were then divided by a flat field.
Wavelength calibration was obtained from comparison spectra taken immediately after
(before and after the KPNO observation) the spectrum of the galaxy. Standard IRAF and
Vista procedures were followed to convert the spectra to a linear wavelength scale. The rms
was \( \lesssim 0.1 \text{ Å} \) for the ESO and Kitt Peak spectra. The instrumental resolution was estimated
measuring the FWHM of faint lines of the comparison spectra. The values are approximately
2 Å, 3.2 Å, 4 Å for the ESO, KPNO and INT observations respectively. Flux calibration was obtained from at least two/three nightly observations of spectrophotometric standard stars. We estimate, from a comparison of the \([\text{OIII}]\lambda\lambda 4959,5007\) flux measurements in different spectra, that the uncertainties in the flux calibration are \(\approx \pm 25\%\) (2\(\sigma\)).

The spectra were scaled to the average of the measured \([\text{OIII}]\lambda\lambda 4959,5007\) fluxes, in order to compare the relative fluxes of the broad lines at different epochs of observations. Although the spectrum obtained at KPNO was calibrated using standard stars observed with a narrow (2.5 arcsec) slit, the results for the narrow lines are in good agreement with the average of the INT observations. We are therefore confident that the calibration is adequate.

The scaling procedure is somewhat arbitrary for the spectrum taken at ESO because the \([\text{OIII}]\lambda\lambda 4959,5007\) lines were outside of the observed spectral range. The flux level in the ESO spectrum is discordant with respect to the others by a large factor \(\sim 2.5\). The discrepancy is too large for us to use it with confidence. It has been used for the analysis of the H\(\alpha\) profile shape since it provides the highest S/N ratio in the H\(\alpha\) region. No line fluxes are reported for the ESO spectrum in Table 2.

Two–dimensional sections of the CCD frames obtained at ESO and at KPNO were wavelength and flux calibrated, to allow for study of possible extended emission in OQ 208.

Uncertainties quoted throughout the paper are at the 2\(\sigma\) level unless otherwise stated.

3 Results

3.1 Line Identification and Line Fluxes

The overall optical spectrum of OQ 208 is shown in Figure 1. The H\(\beta\) and H\(\alpha\) regions of four representative spectra are shown in Figure 2 (after normalization to the same \([\text{OIII}]\lambda\lambda 4959,5007\) flux) at a scale which emphasizes changes in the level of the underlying continuum and variations in the line profiles. The heliocentric radial velocity of OQ 208 measured from \([\text{OIII}]\lambda\lambda 4959,5007\), [NII]\(\lambda 6583\), and the narrow components of H\(\beta\) and H\(\alpha\) is
\[ v_0 = 22985 \pm 15 \text{ km s}^{-1} \]. The absolute line fluxes of the most prominent narrow lines (corrected for galactic reddening) are reported in Table 2. The large shift between the peaks of the broad and narrow components in H\(\beta\) allows us to estimate their relative contributions with high accuracy. The H\(\beta_{NC}\) flux estimates agree within 15% (after normalization to their respective [OIII]\(\lambda\lambda4959,5007\) fluxes and excluding the spectrum obtained in June 1985).

Deblending of the narrow H\(\alpha\) and [NII]\(\lambda\lambda6548,6583\) components from the underlying broad H\(\alpha\) profile was not so easy. Any deconvolution procedure will be highly subjective because the peak of broad H\(\alpha\) is shifted to the red side of [NII]\(\lambda6583\). Differences between the broad H\(\alpha\) and H\(\beta\) profiles make it difficult to use a suitably scaled H\(\beta\) profile as a model template for the broad component of H\(\alpha\). Nevertheless, while not matching the total broad H\(\alpha\) profile, we note that the scaled H\(\beta\) profile reproduces quite well the red wing (see Fig. 2e and 2f and the analysis in § 3.2). This suggests that the shape of broad H\(\alpha\) emission underlying H\(\alpha_{NC}\) and [NII]\(\lambda6583\) is properly taken into account by such a scaling. We repeated this procedure for all of the spectra with reasonable S/N and the deblending yielded very similar results. We find that [NII]\(\lambda6583/\alpha_{NC} \approx 0.98 \pm 0.10\), and H\(\alpha_{NC}/\beta_{NC} \approx 4.1 \pm 0.8\). The internal reddening estimated from the Balmer decrement is therefore E(B–V) = 0.175. Fluxes of the fainter narrow lines reported in Table 2 are believed to be accurate within \(\pm 50\%\). The large uncertainty is a result of the low S/N ratio in the H\(\alpha\) spectral region.

Fluxes of the prominent broad lines and FeII blends are reported in Table 3 along with values for the continuum at \(\lambda4800\) Å. Column headings in Table 3 indicate the dates of observation. The spectrum of OQ 208 is atypical for a BLRG or a Seyfert–1 galaxy if one considers the large peak displacement of the broad Balmer lines. The value of the ratio [OIII]\(\lambda5007/\beta_{NC}\) is however typical for BLRG although rather high for a Seyfert 1 galaxy (Osterbrock, 1978). The [OIII]\(\lambda\lambda4959,5007\) lines show a fainter component displaced 1000 km s\(^{-1}\) to the red. Heckman, Miley & Green (1984) using lower S/N data describe this second component as broad [OIII]\(\lambda\lambda4959,5007\). It is doubtful that broad [OIII]\(\lambda\lambda4959,5007\) could
significantly affect the red side of $H\beta$ in OQ 208. The FeII lines at 4924 and 5018 Å, which are expected to have broad profile similar to that of $H\beta_{BC}$, are clearly present (it is interesting to note that they fall at the positions expected if their peak displacement is the same as the red peak of $H\beta$). These lines can mask any weak broad-line component of [OIII], especially if the FWHM of the broad lines is larger than 3000 km/s (Crenshaw & Peterson, 1986). The $H\beta$ profile resulting from the subtraction of the narrow [OIII] profile and the FeII emission is rather smooth. We conclude that there is no evidence for broad [OIII] emission in the red wing of the $H\beta$ profile.

In the spectrum obtained at Kitt Peak we found no difference between the cross-dispersion Point Spread Function of the continuum and the [OIII]λλ4959,5007 lines. This suggests that the [OIII]λλ4959,5007 emission must arise in an unresolved region within $d \approx 1.6$ arcsec.

FeII emission on the red side of $H\beta$ is clearly visible in the Figure 1 spectrum obtained when OQ 208 was near the bright stage. However, FeII emission on the blue side of $H\beta$ falls below the noise level in many spectra (we will henceforth refer to the FeII emission λ4460-4700 Å and λ5190-5320 Å as the 4570 and λ5250 blends respectively). In Table 2 we give an estimate for the total flux in the FeII blends and an upper limit for the flux when the λ4570 emission falls below the 5σ continuum noise level. The ratio of the total FeII emission to $H\beta$ is not uncommon among Seyfert 1 galaxies and is also not unusual for a compact-core dominated radio galaxy (Joly, 1991; Jackson & Browne, 1991).

The ratio between the FeIIλ4570 and λ5250 blends is in the range 0.14–0.33. This is unusual for a Seyfert 1 galaxy. The average value of the ratio FeIIλ4570/FeIIλ5250 for the 18 Seyfert galaxies measured by Phillips (1978) is $\sim 1.05 \pm 0.25$. Furthermore, assuming a flux ratio between the radio core and lobes equal to $R = 2.3$ (Perez, 1987), the ratio FeIIλ4570/[OIII]λ5007 is low for a compact core radio galaxy (Jackson & Browne, 1991). Since the ratio FeIIλ5250 /$H\beta_{BC}$ is much more typical, we conclude that emission from FeIIλ4570 is unusually low in OQ208. Only Mkn 231, among the objects studied by Phillips
(1978), shows a $\lambda 4750/\lambda 5250$ ratio ($\approx 0.4$) similar to OQ208. This object is one of the three strongest FeII emitters known (see e.g., Sulentic et al. 1990). Internal reddening in Mkn 231 is probably responsible for a steep decrease in the spectrum toward shorter wavelengths. The steep continuum observed in the spectrum of OQ 208 (Fig. 1) suggests that internal reddening may play a role in this object as well. The low FeII ratio could also related to excitation conditions in the FeII emitting zone. In fact, faint emission is suspected in the region 6000–6500 Å, where contributions from multiplets 199 & 200 are expected if the main energy input is provided by photoionization. This result is somewhat peripheral to the present investigation. It requires confirmation by further high S/N observations in the red spectral range.

3.2 Line Variability & Line Profiles

The flux of H$\beta$ underwent remarkable changes by a factor $\lesssim 2 - 2.5$ in the period 1985 and 1991. This is well demonstrated from variations in the ratio $I(H\beta)_{BC}/ I(H\beta)_{NC}$. The value of this ratio increased monotonically from $\sim 15$ in March 8, 1985 to $\sim 40$ in Feb. 19, 1991. We also measured this ratio on an enlarged print of the 1978 spectrum taken by OC79. We found that $I(H\beta)_{BC}/ I(H\beta)_{NC} \sim 40 - 50$, somewhat larger than the value obtained in the 1991 spectrum. Since there is no doubt that this ratio was much smaller in 1985, the line luminosity must have faded between 1977 and 1985 followed by an increase between 1985 and 1991. The variations suggest that the Balmer lines may be described as passing through a high and low luminosity phase. The H$\beta$ flux from the 1991 observation is the largest among our spectra, and we consider this profile as representative of the high phase. Evidence for recurring high and low phases was also found for Akn 120 and IC 4329A (Marziani, et al. 1992). No strong variations in the emission line profiles were observed in these two galaxies and the luminosity changes suggested a shorter time–scale.

The difference between the spectrum obtained on Feb. 19, 1991 (high phase) and the
spectrum obtained from the weighted (over the S/N ratio) average of the spectra taken in 1985 (low phase) is shown in Fig 3. The major changes of the Hβ profile can be described as an increase on the red side of the peak and a remarkable increase of the blue wing. No obvious change occurred in the red wing, a result which should be confirmed due to the [OIII]λλ 4959,5007 emission in this part of the profile.

The principal result of this investigation involves the discovery of a correlation between the Hβ line luminosity and the radial velocity of the red peak. The center of the flat–topped red peak observed in the 1991 spectrum is shifted with respect to the narrow component of Hβ by $\Delta v_r \approx 2600 \text{ km s}^{-1}$ (see Fig. 2e). The spectrum published by OC79 shows a similar value for the velocity displacement. In order to verify that a change in the peak displacement occurred, one can consider that an upper limit to the displacement of the peak in 1985 (see Figure 2a), when the line luminosity was much lower was $\Delta v_r \approx 1500 \text{ km/s}$. A spectrum taken in April 1985 with the 3.0 m Shane telescope at Lick Observatory, and kindly provided to us by R. Cohen, confirms our estimates for the line ratio and the peak shift.

The definition of a peak or centroid radial velocity is by itself subject to ambiguity and to many uncertainties. The situation is made even worse for OQ 208, since the broad Hβ profile at certain epochs is flat–topped, and since the S/N in some spectra is low. We first measured the “centroid” by eye using the peak wavelength of the broad component or the middle of the flat top. In order to analyze the peak displacement in a more quantitative fashion, we also considered the centroid of the red peak weighted on the third power of the intensity for each wavelength interval (see Fig. 4a, where the intensity ratio between the narrow and broad component of Hβ is plotted versus line shift).

Analysis of Figure 4a suggests that the peak shift and line strength are correlated. The limited number of observations, especially at different stages in the variability, prevent us from describing the functional form of the correlation. We note that variations in flux and shift occurring in 1985 and 1986, as well as in 1988 and 1989, are not much larger than the
observational uncertainties. Significant changes appear to occur only between 1986 and 1988 and between 1989 and 1991. Data appear to be correlated irrespective of the definition of the centroid. However, the amplitude and shift change somewhat depending upon the choice of the window over which the centroid is computed.

Figure 4b shows the H$\beta$ peak displacement plotted against the normalized intensity measured between H$\beta_{NC}$ and the [OIII]$\lambda$5007 line. This is equivalent to measuring the line flux emitted within a radial velocity interval equal to $\approx \pm 0.13$ HWZI. This will, consequently, exclude a significant contribution from the line wings and will emphasize the variation of the red peak. We favor this procedure because the velocity frame for the flux measurements should be set at the radial velocity of the redshifted peak. We just avoid that the origin will be different at each epoch because the redshift of the peak is changing. The data are correlated with approximately the same degree of confidence. This suggests that the red peak is probably related to an independent component which varies more strongly than the rest of the line. This interpretation is supported: (1) by the shape and lower redshift of the broader part of the H$\beta$ profile and (2) because the percentage of variation in the broad component is smaller than for the red peak. Figure 4c shows the H$\beta$ shift versus the continuum flux at 4800 Å. Although the estimate of the continuum flux is sensitive to the uncertainties in the spectrophotometric calibration, the data show a correlation.

Analysis of the H$\alpha$ profile is made difficult by the large spread in S/N among the red sensitive spectra. The strength and shape of the blue wing on the H$\alpha$ profile has probably varied in the spectra taken at different epochs. The shape of the blue wing in H$\alpha$ and H$\beta$ was similar when the line luminosity was near minimum (1985–1986). The blue wing of H$\alpha$ appears to have increased in strength relative to the red one in the spectra taken after 1988. This result is supported by the change in the blue-wing of H$\beta$ shown in Fig. 3, but it remains uncertain to some extent since the H$\alpha$ region in the INT spectra was not corrected for B-band absorption. If we compare the profiles of H$\beta$ (Feb. 19, 1991, Fig 1e) and H$\alpha$ (Apr. 4, 1990,
Fig. 1f) we note that the shape of the red wings in both lines are very similar except that the blue side of Hβ lacks the hump clearly visible in Hα. This suggests at first that the Balmer decrement is steeper in the gas emitting the blue part of the line.

The blue wing of Hα takes the form of a peak in the ESO (1990) spectrum. Note that this blue peak is also present in OC79. This feature is probably real, although it is not clearly seen in the spectra obtained at the INT. We note however that the blue side of the Hα profile is heavily contaminated by the telluric B–band absorption. The ESO spectrum was corrected for B–band absorption by using observations of a standard star observed at a similar zenith distance immediately after OQ 208. This was not possible for the other spectra.

4 Discussion

The observation of a large redshift for the broad Balmer lines suggests an AB,R classification (i.e., blue asymmetric profile with redshifted peak) for OQ208 according to the scheme proposed by Sulentic (1989). This appears to be a rare class. On the contrary, AR, B profiles appear to be quite common. Of the 61 objects included in Sulentic (1989) only I Zw 1 was assigned type AB,R. The redward displacement of the broad component in I Zw 1 (ΔV ≈ 640 km/s) is much less than for OQ208. I Zw 1 also shows a much narrower profile that is contaminated with strong FeII emission. The two objects show a similar displacement expressed in units of their respective profile FWHM. The degree of profile asymmetry in I Zw 1 is not nearly as pronounced (asymmetry index of 0.07 compared to 0.2 for OQ208). If the AB,R classification reflects similar geometry in these two objects, then the FWHM of the Balmer lines is somewhat independent of geometry considerations.

A number of objects with peculiar line profiles have been studied by various authors in the past few years. A partial list includes 3C390.3, 3C382, Arp 102B, 3C332, OX 169, Akn 120, IC 4329A (see Marziani 1991 for spectra and references). The objects listed above can be divided into two subgroups: I) OX 169, Akn 120 & IC 4329A show a redshifted peak in
addition to a peak located at approximately the same redshift as the underlying galaxy (a small blueshift of $\approx 100 – 300 \, \text{km s}^{-1}$ is suspected for this “zero” peak); II) Arp 102B, 3C332, 3C390.3, 3C382 show two prominent peaks roughly symmetrically displaced with respect to the systemic radial velocity. Apparent differences between objects of the same subgroup exist, particularly as far as variations in the profiles are concerned. Prototype objects with a double peaked profile, Arp 102B (Chen & Halpern, 1989, and 3C332 Halpern, 1990) show rather stable emission features. Although the possibility of variations have been suggested (Halpern & Filippenko, 1988; Miller & Peterson, 1990), they appear to be small and not comparable with the changes observed in the H$\beta$ profiles of 3C390.3 and 3C382 (Perez 1987; Perez et al. 1988). OQ 208 is somewhat unique in that it shows only a red peak, although its H$\alpha$ profile resembles the profile observed in 3C390.3. The similarity with 3C390.3 (cf. Figures 5.13 of Perez 1987) holds only at certain epochs: 1) variations of the line profiles in 3C390.3 are of larger amplitude and occur on a shorter timescale than variations in OQ 208 (e.g., Veilleux & Zheng, 1991) and 2) unlike OQ 208, the spectra of 3C390.3 show a more prominent blue peak at certain epochs. A 900 km/s change in the blue peak displacement has also been observed. Veilleux & Zheng (1991) and Zheng, Veilleux & Grandi (1991) suggest that the variations in strength and peak displacement may be due to the changing position of a hot spot on the disk. We will discuss later the relevance of this model to the case of OQ 208.

We propose to model the BLR structure of OQ 208 taking advantage of the main observational facts established in this investigation:

1. the flux of the Balmer lines varied by a factor of 2–3 between 1985 and 1991;

2. the red displaced broad component peak remains the most prominent feature in the H$\alpha$ and H$\beta$ profiles at all epochs of observation;

3. the radial velocity of the red peak in H$\beta$ is correlated with the line luminosity.

OC79 proposed that the large redshift of the Balmer line peaks in OQ208 was
gravitational in origin. The addition of gravitational and transverse redshift can lead to
\[ \Delta z \approx \frac{3 R_g}{2 R}, \]
where R is the distance of the emitting gas from the central black hole, and
\[ R_g = \frac{2GM_{BH}}{c^2} \approx 2.95 \times 10^{12} M_{BH,7} \text{ cm} \]
the gravitational radius of the black hole. The redshift is however too large to be entirely due to
the gravitational field of the black hole. The shift \[ \Delta v_r \approx 2600 \text{ km s}^{-1} \]
would imply that the bulk emission of the line takes place at \[ R \lesssim 150 R_g \approx 4.38 \times 10^{14} M_{BH,7} \text{ cm}, \]
an implausibly small distance between the BLR and black hole. It would be a factor 5–7 below estimates
from photoionization calculations, and smaller than the inner radius of the BLR estimated
from cross–correlation analysis, even assuming anisotropic line emission (e.g., Rees, Netzer &
Ferland, 1989; Ferland et al. 1992).

The “hot spot” interpretation also faces serious difficulties. If we accept the nearly face-on
orientation of the disk implied by the R parameter, it is not clear how to explain a lower
luminosity when the displacement is smaller. Obscuration of the rotating spot by the disk
itself could in principle explain this result but obscuration plausibly occurs only if the disk is
seen nearly edge-on. In addition, changes in radial velocity due to radial drift of the hot spot
are expected to occur on timescales which are much longer than the Keplerian timescale for a
geometrically thin disk.

It seems more realistic to ascribe the large peak redshift to bulk motions of the BLR gas.
The observation of a shifted broad component in H\(\alpha\) and H\(\beta\) points toward a predominance of
radial motion over rotational or random motions in a virialized ensemble of clouds. The
unusually large value of the shift probably points toward an extremum in the viewing angle of
the AGN: i.e., the bulk emitting gas should move in a direction along (or at least not too far
from) the line of sight.

Ideas regarding orientation indicators for the central engine of AGN deserve some
discussion at this point. Orr & Browne (1982) suggested that the appearance of a radio
source is governed by the viewing angle of the observer with respect to the radio axis: if the
radio galaxy is observed pole-on, we see a compact core dominated source and if the source is observed edge-on, we see a lobe dominated source. A relevant implication of this view is that the radio morphology can be used as an “aspect indicator” and that it provides an estimate of the inclination at which the radio axis is observed with respect to the line of sight. This procedure also gives the orientation of the accretion disk assuming that the plane of the disk is perpendicular to the radio axis. In our case, the compact radio source associated with OQ 208 would imply that the disk is seen nearly face on. The parameter R defined by Orr & Browne (1982) is thought to be the most reliable inclination estimator available and in the following we will consider with some confidence the assumption of an accretion disk oriented face on in OQ 208.

5 Non–Radial Considerations

A coarse trend between H\(\beta\) FWHM and the R parameter for BLRG (objects with the broadest Balmer line profiles tend to be lobe dominated sources, Wills & Wills 1986) suggests that the Balmer lines are emitted in a plane perpendicular to the radio axis and, possibly, by the accretion disk. This trend is not well established since, for each value of R (and hence for each disk inclination) there is a large spread in FWHM.

Apart from the heuristic considerations outlined above, the observation of a red peak much stronger than a blue one disagrees with the predictions of simple relativistic disk models. This makes it very difficult to argue that the entire Balmer line emission of OQ 208 originates from a Keplerian disk. Relativistic accretion disk models produce line profiles with an enhanced blue peak (due to Doppler boosting) and a slightly redshifted line base (due to the combined effects of gravitational and transverse redshift; Mathews, 1982; Chen & Halpern, 1989). We have noted that the blue wing of H\(\alpha\) in OQ208 can be much stronger than the blue wing of H\(\beta\) and that the blue wing of H\(\alpha\) has the form of a broad hump in the 1990 spectrum (and in OC79). If the blue hump is assumed real and is interpreted as arising from a radiating disk, a
relativistic disk model profile can be made to fit the broad component of H\(\beta\) (with power-law emissivity of index \(q = 3.2\), \(R_{\text{in}} = 200R_g\), \(R_{\text{out}} = 1250R_g\), inclination \(i = 37^\circ\), with \(i = 0^\circ\) corresponding to a disk oriented face-on). The addition of a redshifted component, needed to explain the red peak, provides a satisfactory reproduction of the broad component of H\(\alpha\) as observed in 1990. A disk model profile able to reproduce the form of the blue H\(\alpha\) hump suggests that the disk emission would contribute about \(\approx 2/3\) of the H\(\alpha_{BC}\) flux. If we assign most of the red peak to an independent component and accept the reality of the blue peak in H\(\alpha\) the profile observed in 1990 can be made consistent with an accretion disk model.

Another possibility to consider before discussing radial motion is that the large displacement of the red peak in H\(\beta\) is due to the orbital motion of a binary black hole. Two constraints are relevant to this model: a) spectra exist for the period 1985-91 and b) a lower limit to the variation in peak radial velocity is \(\Delta v_r \approx 1000\) km/s. This suggests that the phase change of the binary should be: \(\Delta \Phi = \arccos(1 - \Delta v_r / v_r) \approx 53^\circ\) which implies that the period is \(\approx 37\) yr, and that the mass of the binary is \(M_{BH} \gtrsim \frac{1}{338}PV_{r,1000}^3 \approx 1.7 \times 10^8 M_\odot\).

There are three observational points listed near the beginning of this section that argue strongly against this result. The second point makes it necessary to assume that the center of mass of the binary has a different radial velocity from the reference frame of the underlying galaxy. The third point is perhaps the strongest argument against the binary idea. In the binary model, changes in the line \(\Delta v_r\) should only be related to the orbital motion of the binary black holes, and should not be correlated with changes in the line or continuum fluxes.

6 Radial Considerations

6.1 General constraints

The above considerations point towards radial motion as the most likely cause of the red peak in OQ208. The observed correlations between the peak redshift and line and continuum fluxes (Fig. 4a, 4b and 4c) indicate that the velocity field is probably (although not necessarily, as
discussed below) coupled to the continuum luminosity of the object. Furthermore, the correlation rules out the possibility that the line emitting gas can acquire its momentum on a time scale short compared to the time scale of the variation; i.e., the motions of the clouds can not be ballistic.

We must next consider whether the motion of the clouds is directed inward or outward. We can imagine a system of clouds surrounding the accretion disk. If the disk is oriented pole on, as we have proposed for OQ208, we might be able to see clouds located on the nearer side of the accretion disk preferentially. In this case emission from the clouds would only be redshifted if the clouds were infalling. The clouds moving at the highest velocity should be located closest to the central source if they are freely falling in the potential well of the black hole. This would not necessarily be true if the effect of radiation pressure is taken into account. The clouds would move at lower velocity when they are closer to the central source if radiative deceleration overcomes gravity (e.g., $k < 0$ in Eq. 2 of § 6.2). In principle, clouds could approach the central source and be pushed away by radiation pressure. This scenario leads to a prediction that contradicts our observations (point 3 above): if radiation pressure decelerates infalling clouds, an increase in the continuum luminosity would enhance the radiation pressure and the line luminosity, but it would also lead to a decrease in the velocity $\Delta v_r$ of the infalling gas.

If the clouds are radiation–bounded and the continuum luminosity changes, we expect a change in emissivity (occurring first for clouds closest to the continuum source) without any appreciable change in the velocity field. If this case is applicable, and radiation pressure is negligible, the gas moving at higher velocity (located closest to the continuum source) simply has a stronger response than the gas moving nearer to the peak velocity. This touches on a basic problem in the understanding the BLR. It is unclear whether the structure of the BLR changes appreciably in response to strong continuum changes. In the following we will assume that the effects of radiation pressure are likely to be significant.
The case for infall remains appealing also because of the redshifted secondary component in [OIII]λλ4959,5007. This feature is suggestive of infall (see e.g., Rafanelli & Marziani, 1992, for a case in which [OIII] lines show a strong redward asymmetry, and for which infall has been established). If there is a continuity between the properties of the gas in the NLR and in the BLR, as several arguments suggest (e.g., Appenzeller & Ostreicher, 1988), both the NLR and BLR could be infalling toward the central source.

If the gas emitting the Balmer lines is optically thick to the ionizing continuum, changes in the line fluxes are proportional to changes in the continuum. Morris & Ward (1988) and Zheng (1991) have shown that the Balmer lines of several AGN are emitted by optically thick gas with the possible exception of the far wings, so that it is legitimate to assume that, at least, the red peak of Hβ is emitted by optically thick gas. Recent results by Ferland et al. (1992) support this point of view and suggest that the BLR clouds radiate anisotropically. The correlation between shift and line intensity suggests that radiation pressure is dynamically important.

The observation of a red peak stronger than the blue one poses some difficulties, if we do not rely on optical depth effects for the Balmer lines. The stronger peak should be the blue one in this case – the contrary of what is observed. Thus, the gas can be accelerated outward by radiation pressure only if the optical depth is very large in the Balmer lines or if dust on the back of clouds absorbs the outcoming radiation – allowing Balmer photon to escape preferentially from the illuminated face of the clouds. It has been usual in the past years to ignore optical depth effects in the Balmer lines when computing profile models. The second level of hydrogen inside the BLR is overpopulated because of Lyα trapping and, as a consequence, the optical depth in the Balmer lines is expected to be high. The escape probability of a Balmer photon from the non-illuminated face of the cloud should in turn be very low (Ferland et al. 1992).

This motivates us to model the profile of Hβ (as observed in 1991) under the assumption
that the line is emitted by a system of clouds moving radially outward under the combined
effects of radiative and gravitational forces. We assume a biconical geometry (which includes
the case of a spherically symmetric system if the half opening angle of the cone is $\theta \approx 90^\circ$).

The correlation shown in Figure 4b suggests that the increase in continuum luminosity
produces an enhancement of a radially moving component. The red peak varies more strongly
than the broader base. The presence of two components in H$\beta$ is supported by the shape of
the profile, which shows an inflection at the base of the red peak. Moreover, the profile
difference between the high and the low phase (Fig. 3) shows a narrow peaked feature which
is responsible for the increase in the centroid shift.

Our interpretation of the variations observed in H$\beta$ and of the best fit to the line profile
(described in the next section) have several analogies with the findings of Ulrich et al. (1985)
concerning the appearance of emission features on the blue and red side of CIV$\lambda$1549. The
“satellite” lines to CIV$\lambda$1549 were interpreted as emission coming from BLR clouds trapped in
a jet. We interpret the second component of H$\beta$ in basically the same way. We interpret that
lack of a blue “satellite” as due to the emission anisotropy and the orientation of OQ 208.

6.2 The model

The previous discussion of broad line profile shapes, and consideration of various models,
favors a scenario in which outflowing clouds are driven by radiation pressure (e.g., Blumenthal
& Mathews, 1975). This model is not devoid of theoretical difficulties, since the existence of
clouds requires a hot, less dense confining medium with which the clouds should be in
pressure equilibrium. Drag forces and hydrodynamical instabilities could lead to cloud
disruption in a time shorter than the dynamical timescale (Mathews & Ferland, 1987;
Mathews & Veilleux, 1989). The confining medium should give rise to some signature in the
X–ray spectrum. This is not observed in the spectra of Seyfert galaxies and quasars (Mathews
& Ferland, 1987, Osterbrock 1991).
The equations of motion for clouds moving under the effect of radiative and gravitational acceleration was studied by Blumenthal & Mathews (1975). In the following discussion we assume that the acceleration due to optical and infrared radiation is negligible compared to that from the ionizing radiation. The question of whether the clouds are outflowing or infalling depends upon the acceleration parameter, namely

\[ k = \frac{A_c \int_{\nu_0}^{\infty} L_{\nu} d\nu}{4\pi c M_c} - GM_{BH} \quad (1) \]

where \( A_c \) is the area of the cloud exposed to the ionizing continuum, \( \nu_0 \) is the Rydberg frequency, \( L_{\nu} \) is the specific luminosity of the ionizing continuum, \( M_c \) is the mass of a single cloud, and \( M_{BH} \) is the black hole mass. The expression for \( k \) can be rewritten in a more convenient form:

\[ k = \frac{\int_{\nu_0}^{\infty} L_{\nu} d\nu}{4\pi c \mu N_c} - GM_{BH} \quad (2) \]

where \( N_c \) is the column density, and \( \mu \) is the mean molecular weight. Holding \( M_{BH} \) as a free parameter, the latter equation contains quantities which can (in principle) be estimated from observations in a straightforward manner. We assume in addition that \( M_c \) and \( N_c \) \((\sim 7 \times 10^{22} \text{ cm}^{-2})\) do not change during the cloud’s motion. This might not be a realistic assumption if drag effects alter the shape as well as the mass of a cloud (Mathews & Veilleux 1989). Unfortunately there are no direct observations of the ionizing continuum in OQ 208 that are available to us. We are therefore forced to a somewhat indirect estimate of the ionizing luminosity. We deduced the number of ionizing photons emitted by the continuum source from the reddening corrected H\( \beta \) luminosity assuming a covering factor of \( f_c \approx 0.17 \), which is the average value for the Seyfert galaxies studied by Padovani & Rafanelli (1988).

We then calculated the ionizing luminosity assuming the spectral shape of the ionizing continuum has the form considered by Netzer (1990). We obtained \( L_{\text{ion}} \approx 5.9 \times 10^{44} \text{ h}^{-2} \text{ erg s}^{-1} \) \((H_0 = 100 \times h \text{ km s}^{-1}\text{Mpc}^{-1})\). It follows that outflow is possible \((k > 0)\) if the black hole
mass is \( M_{BH} \approx 2.3 \times 10^7 \ h^{-2} \ M_\odot \). A mass of 10^7 \ M_\odot \ is plausible for OQ 208 since its ionizing luminosity gives a value for the Eddington ratio that is within the limits set by the estimates of Padovani & Rafanelli (1988).

The equation of motion yields a velocity field of the form:

\[
 u(r) = \sqrt{A - \frac{2k}{r}}
\]

in the case of outflow (\( k > 0 \)), where \( A = 2k/R_1 \), and \( R_1 \) is the inner radius of the BLR. This function is typical of outflowing winds (e.g., Wallerstein et al. 1984).

The integral equation relating the line profile \( P(\lambda) \) to the emissivity, the cloud density and the velocity field can be written as:

\[
P(\lambda) = 2\pi \int_{R_{min}}^{R_{max}} \int_{-\Theta_0}^{\Theta_0} r^2 \sin \theta d\theta dr j_c(r) n_c(r) \delta[\lambda - \lambda_0(1 + u(r)\xi/c)]
\]

where the opening angle of the cones is \( 2\Theta_0 \), and the BLR is assumed to extend from \( R_{min} \) to \( R_{max} \), and \( \xi = \cos \theta \), is the cosine of the angle between the line of sight and the velocity vector of each cloud. In principle, the number density of clouds \( n_c(r) \) can be computed from the continuity condition \( n_c u(r) r^2 = \text{const} \). Since this law probably breaks down at the inner edge of the BLR where the clouds are assumed to form, we considered also power-law functions for \( n_c(r) \), namely \( n_c(r) = n_0 (r/R_{min})^{-m} \). Template profiles have been computed assuming that the cloud emissivity \( j_c(r) \) is again a gaussian or a power-law

\( (j_c(r) = (r/R_{min})^{-m}, \text{with } m = 1, 2, 0, -1) \). A grid of profiles was computed for different values of \( \Theta_0 \) and inclination of the cone axis with respect to the line of sight (\( i \)). The inner edge of the BLR was estimated at \( R_{min} \approx 10^4 R_g \approx 2.95 \times 10^{16} M_{BH,7} \ M_\odot \ \text{cm} \), while the outer radius was set at \( R_{max} = 10^5 R_g \). The parameter \( k \) was computed assuming \( M_{BH} = 10^7 \ M_\odot \), \( N_c = 7 \times 10^{22} \text{cm}^{-2} \). We further assume that the clouds are accelerated from rest.

We remark that the two main conditions which must be satisfied are that: (1) the peak of the profile is displaced and (2) the peak is nearly flat. In order to achieve a global shift of the
We assume that the approaching half of the flow contributes little or no emission. If the emission of the Balmer lines is intrinsically anisotropic (see e.g., Ferland et al. 1992 or Zheng, Binette & Sulentic, 1990, where the effect of anisotropy is maximized since the opening angle of the cone is assumed small and the line of sight close to the cone axis), there is little or no need to introduce any additional source of obscuration. The effect of the anisotropy is assumed to be proportional to $\sin(\theta/2)$ and $\sin(\theta/2 + \pi/2)$ for clouds located on the near and far side of the continuum source respectively.

Single component models (including anisotropy) produce profiles which are roughly similar to the observed $\text{H}\beta$ profile of OQ 208. We were unable however to satisfactorily fit the details of the profile. It is interesting to note that clouds in a curved jet would also give rise to profiles with shift and asymmetry similar to those observed in OQ 208 (Wallerstein et al. 1984). We did not attempt a fit in this case.

We modelled the lines as made up of a component emitting the broad wings and another emitting the red peak (see Fig. 5). The shape of the broad wings suggests that the line base is emitted by a spherical ensemble of clouds surrounding the central engine. This result is not strongly dependent on the velocity field or emissivity. We note that the inclusion of anisotropic emission lead us to a very good reproduction of the asymmetry and line shape of $\text{H}\beta$. Satisfactory fits can be obtained if the clouds are confined in a sphere (as is the case for the fit shown in Fig. 5) or in a spherical section of half thickness $\theta > 60^\circ$. The second (radial) component is probably made up of a thin shell of matter being pushed away in a jet–like configuration, where the emissivity decreases from the inner to the outer edge of the shell. Again, the best agreement with the observations is obtained in the case where the effect of anisotropic line emission is included. The best fit is obtained with a shell of thickness $t < 3R_{\text{min}}$ in a cone of half–aperture $\Theta_0 \approx 12^\circ$ and seen at $i = 0^\circ$. The emissivity is represented by a gaussian peaked at $r = R_{\text{min}}$, with $2\sigma^2 = 0.181 R^2_{\text{min}}$, and where the number of clouds decreases as $\propto r^{-5}$. We obtain however model profiles with blue wings and roughly...
flat tops for both power–law and gaussian emissivity, with \( \Theta_0 = 12^\circ \), in some cases with \( i \) up to \( \sim 30^\circ \). A very weak blue hump (due to the approaching gas in the double stream) should be seen on the blue wing of H\( \beta \) if anisotropy is the only thing taken into account. This would correspond to a 4\( \sigma \) feature which could be suppressed by a small amount of extinction due to dust on the non illuminated face of the clouds or even be lost in the absorption features contaminating the blue wing of H\( \beta \).

We note that it is also possible to roughly reproduce the observed profiles assuming that gas is infalling and decelerated by radiation pressure. However, in light of the analysis of the BLR dynamics outlined above, infall is not favored by the variations of the line.

7 Conclusions

The most likely explanation for the complex Balmer line profiles of OQ 208 involves outflow of the emitting gas probably radiatively accelerated in a biconical geometry, plus emission from an ensemble of clouds which might be spherically symmetric or confined in a thick cylinder. Emission from infalling gas and/or from a rotating disk (heavily obscured) is not favored by our analysis, but cannot be ruled out and remains a competing alternative. Optical depth effects in the Balmer lines must be taken into account to properly understand the asymmetries observed in the line profiles. Several important questions follow from the present investigation. The most important are related to the peculiarity in the FeII emission, and to the existence of an obscured or self absorbed line component.

Observations with Hubble Space Telescope would allow us to measure radial velocities for the strongest high ionization lines that are located in the ultraviolet. They would clarify whether there is also a systematic shift between LIL and HIL for Seyfert galaxies. Some predictions are possible on the basis of the model outlined in the previous section. If the red peak of the Balmer lines arises in an outflowing component we do not expect to see a redshift difference between the HIL and LIL. If the LIL arise from infalling clouds we expect to see a
large velocity difference between the HIL and LIL. In the latter case the HIL and LIL would arise from opposite sides of the BLR and from opposite faces of the clouds. A UV spectrum for OQ208 would therefore provide an unambiguous test of our model.

Spectroscopic monitoring of OQ 208 would lead to other valuable information. Temporal sampling in the interval from one to a few months would constrain the line response to continuum changes. We observed variations in the red hump as well as in the blue wing of $\text{H}\beta$. Adequate monitoring would allow to determine whether such changes occur simultaneously and if not, which occurred first. The strong variations observed in the line profiles of OQ208 (occurring on a rather long timescale) suggest that monitoring holds promise of a large return from relatively few observations covering a period of few years. Although OQ 208 is relatively faint, with present instrumentation it is possible to obtain high S/N spectra (as demonstrated by the Kitt Peak spectrum employed in this study). OQ208 may be one of the first AGN for which an unambiguous model of the BLR is possible.

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10 Figure Captions

Fig. 1: The spectrum of OQ 208 obtained on 1989 July 31. Horizontal scale is wavelength in Å, vertical scale is flux in units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$.

Fig. 2: H$\beta$ and H$\alpha$ profile of OQ208 at different epochs (a) and (d) 1985 Jun. 15, (b) and (e) 1989 Jul. 31, (c) 1991 Feb. 19. and (f) 1990 Apr. 04. All spectra have been normalized to the same [OIII]$\lambda\lambda$4959,5007 flux, with the exception of the spectrum taken on 1990 Apr. 4 has been arbitrarily scaled to roughly match the continuum level of the 1991 Feb. 19 spectrum. Units are as for Fig. 1. Vertical and horizontal scales have been chosen in order to evidentiate the variations in the continuum as well as in the line profiles. Note that B–band absorption heavily contaminates the blue wing of H$\alpha$ of the profiles in panels (b) and (d). Correction for B–band absorption has been applied only to the profile shown in panel (f).

Fig. 3: H$\beta$ profile difference between the spectrum taken on 1991 Feb. 19 and the weighted average of the spectra obtained in 1985. Units are as for Fig. 1.

Fig. 4: Correlations between H$\beta$ and continuum fluxes and shift. Vertical scale is radial velocity difference (in km/s) between the centroid of the red hump of H$\beta$ broad component (see text) and peaks of the narrow component of H$\beta$. (a) Horizontal scale is ratio flux of total H$\beta_{BC}$ flux and H$\beta_{NC}$ flux; (b) horizontal scale is approximately flux within $\pm$ 13 % HWZI of H$\beta_{BC}$ normalized by the H$\beta_{NC}$ flux; (c) horizontal scale is specific flux of the continuum at 4800 Å. Open circles: centroid defined by eye estimate; filled circles: centroid defined as weighted average of wavelength over the third power of the intensity. Error bars refer to 1$\sigma$ level of uncertainty.

Fig. 5: Best fit of the H$\beta$ profile observed in Feb. 1991. Dotted line: fit to the red hump + line base. Dashed line: fit to the line base. The straight dot–dashed line indicates the position of the narrow component of H$\beta$, which has been removed.