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PROBING INTERMEDIATE SEYFERT GALAXIES BY Paβ SPECTROSCOPY

HANS-WALTER RIX
Steward Observatory, University of Arizona

N. P. CARLETON
Center for Astrophysics

AND

GEORGE RIEKE AND MARCIA RIEKE
Steward Observatory, University of Arizona

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ABSTRACT

We present high-resolution spectroscopy at Paβ of a sample of nearby Seyfert galaxies. These objects have been selected because of their observed steep Balmer decrements. We demonstrate the usefulness of Paβ in untangling whether dust obscuration or radiative transfer effects cause the large observed Hα/Hβ ratio and find that either mechanism can be dominant. In the cases where dust obscuration is present we find that the dereddened line strengths, relative to the hard X-ray flux, coincide with those found in unreddened objects. We propose a model for the dust distribution which accounts naturally for the frequency of severely reddened AGNs and their amount of reddening.

Subject heading: galaxies: Seyfert

I. INTRODUCTION

Our picture of an active galactic nucleus will depend strongly upon the amount of dust that lies close to it. We may see the nonthermal source, the broad emission-line region, or the narrow emission-line region through obscuration levels ranging from negligible to overwhelming, depending on the scale and geometry of the dust distribution. This dust will contribute thermal radiation in the infrared at wavelengths that might range anywhere from 2 μm to beyond 60 μm, depending on the solid angle covered by dust and on the flux of radiation that it intercepts. Thus, the observed continuum and the emission line spectrum throughout virtually the entire ultraviolet, optical, and infrared can be influenced by dust, perhaps sufficiently that the underlying processes defy recognition. A specific difficult issue is the conditions in the region emitting hydrogen recombination lines. It is typical for both the Balmer decrement and the Balmer-Lyman ratios to be steeper (redder) than predicted by simple recombination theory for optically thin gas, hereafter case B. Calculations of emission-line strengths influenced by radiative transfer in clouds at high gas densities can reproduce many of these effects, but reddening by dust also mimics the observed trends. These two extreme models and more complex ones that combine the effects of radiative transfer and dust reddening can only be tested by measurements of additional recombination lines. Fortunately, additional observational constraints can be obtained from the Paschen series. As shown in Figure 1 of Hubbard and Puetter (1985), for instance, the ratio of Paα/Hα is strikingly less sensitive to differences in excitation conditions than is the Balmer decrement. Similarly, unpublished calculations by R. C. Puetter (private communication) indicate that the strengths of the high level lines observed in the IR typically fall close to case B, regardless of the excitation conditions. Measurements have been made previously on Paα, e.g., Lacy *et al.* (1982), Carleton *et al.* (1984), and Fabbiano *et al.* (1986), who showed that the Balmer decrements were probably strongly influenced by reddening in many active galaxies. Lacy *et al.* (1982), McAlary *et al.* (1986), Rudy and Willner (1983), and Cutri, Rieke, and Lebofsky (1984) presented Paschen and Brackett line measurements of a few galaxies that were difficult to explain by simple reddening models, particularly Mrk 231, NCG 1275 VZw 317, and Mrk 6. Most of these cases are characterized by extremely steep Balmer decrements, suggesting that galaxies with similar behavior might be found by searching among this type of object. However, because Paα at its rest wavelength falls in strong atmospheric absorption; it is observable from the ground only poorly, if at all, in the spectra of most nearby Seyfert galaxies. Fortunately, Paβ is readily accessible and relatively bright. This paper reports new high-resolution measurements on the Paβ emission lines of a set of active galactic nuclei (AGNs) known from previous observations to have unusual optical line ratios: NGC 2110, NGC 2992, NGC 5506, Mrk 6, Mrk 744, Mrk 334, Mrk 609, and Mrk 423. Many of these objects show both narrow and broad line components of comparable strength. Therefore it is mandatory to obtain data with sufficiently high spectral resolution to analyze the narrow-line region (NLR) and the broad-line region (BLR) separately.

The paper is organized as follows: § II describes the observational procedures and the data analysis. In § III we interpret the line flux ratios found for the individual objects in terms of dust obscuration and radiative transfer effects, and in § IV we try to synthesize these results in the context of a dust model. Section V summarizes the results.

II. NEW OBSERVATIONS

a) *Instrumental Setup*

Our observations were taken at the Steward 2.23 m Telescope and the Multiple Mirror Telescope[1] during five observing runs between 1988 October and 1989 September. All spectra were measured with a grating spectrometer that uses

[1] The Multiple Mirror Telescope is a joint facility of the Smithsonian Institution and the University of Arizona.

two 32 element linear arrays of germanium diodes as detectors, read out by JFET integrating amplifiers. The combination provides read noises of ≈ 100 electrons, quantum efficiencies greater than 50% between 0.9 μm and 1.5 μm, and dark currents below 10 electrons s^{-1}. The incoming light is projected onto the two detector arrays through round apertures that have diameters of 2".2 and 6" and are separated by 22" and 60", respectively on the MMT and 2.23 m. The individual pixels fill this aperture, so on neither telescope is the noise degraded by a necessity to combine pixels into a single resolution element. Two gratings provide resolutions of ≈ 400 and ≈ 1500; even at the high resolution, the instrument operates near the photon background limit over much of its spectral range.

Data were obtained by centering the galaxy nucleus in one of the instrument apertures. After an exposure of typically 60 s, the telescope was wobbled to center the nucleus in the other aperture, and a second exposure was obtained. The sequence repeated. This strategy provides virtually a 100% exposure time efficiency, while monitoring the sky continuously, to minimize the effects of rapid variations in the airglow lines on the final sky-subtracted spectra. The observation sequence was continued until adequate signal to noise had been obtained, usually after 5–30 minutes. We will discuss the reduction and analysis of these data in the following section.

b) *Data Analysis*

The data reduction is straightforward. Up to the final stage of the data processing the data from each array are reduced independently. After eliminating deviant readouts, we subtract the sky using the average of adjacent wobbling cycles. This procedure leaves us with a number (typically three to 15) of sky-subtracted spectra which are then scaled to the average of their median pixel values and co-added. Co-adding these spectra gives us a good opportunity to estimate the noise in the combined spectrum by calculating the formal variance of the readouts at each pixel. Subsequently the same procedure is repeated for a bright "flat-field" star near the object on the sky. Ideally, this star should have a featureless spectrum in the spectral region of interest; for Paβ we chose spectral types F8 to G5. This stellar spectrum is used both to flat-field the object spectrum by correcting for pixel-to-pixel variations in the detector sensitivity and to remove atmospheric absorptions. Finally the flat-fielded spectra from the two detector arrays (which are in "units" of the flat-field star) are combined into a single spectrum. In the present set of observations the spectra are flux-calibrated using photometric parameters of the flat-field star (m_V, $J - V$ and $T_{\rm eff}$). Wherever possible we checked this calibration against J band photometry, obtained from the literature, of the same objects measured through a comparable aperture. The agreement is typically within 10%–15%. Since we are not interested in velocity measurements the wavelength calibration is only determined from the grating tilt. As a consequence, the wavelengths are only accurate to ~ 1 pixel.

The equivalent widths of the emission lines, mostly Paβ, were measured with a line-fitting routine written by R. Saffer. In the cases where the line did not show a two-component structure we adopted the EW of the best-fitting Gaussian. In the cases where we were able to decompose the line into a narrow and broad component, we proceeded in the following manner: First, we checked that a single Gaussian fit was unacceptable. Subsequently, we fitted two Gaussians simultaneously, employing two boundary conditions: (1) The width of the narrow component must not significantly exceed the width of the larger of its measured optical counterpart (e.g., Hα) or the width of the instrumental resolution profile. (2) The centroids of both components must not differ substantially. There are several ways to assess the robustness of the decomposition. First, the software returns formal errors which have been found to be reasonably accurate (within a factor of 1.5). Second, we ensured that the program yielded the same decomposition starting from different initial guesses. Third, we compared decompositions of independent spectra of the same object. Finally, we made sure that the sum of the EWs from the two components added up to approximately the total equivalent width as determined from an independent low-resolution spectrum. The largest systematic uncertainty in this procedure arises from the assumption that the line profile can be represented as a superposition of two Gaussians. Some of the spectra are shown in Figures 1–4. Table 1 summarizes the line strength measurements for the narrow and broad components of Paβ, and Table 2 lists line fluxes for the corresponding Balmer lines, compiled from the literature.

III. DISCUSSION OF INDIVIDUAL GALAXIES

Our goal is to use these measurements to estimate the reddening and the location of any obscuring dust. The Paβ line measured at the relatively high resolution and signal to noise of our data is useful for qualitative comparisons with the line fluxes in the Balmer series. Quantitative comparisons are somewhat hampered by the failure of most published theoretical line intensity models to include Paβ. However, Avrett and Loeser (1988) did include the line and calculated accurate models that included a solution of the line transfer equations in detail (their models 6 and 6a). Although these models showed very steep Balmer decrements (Hα/Hβ = 6.0), their prediction of Paα/Paβ ≈ 1.7 is virtually undistinguishable from the case B value of ≈ 1.9–2.1 (Osterbrock 1989; Wynn-Williams 1982), suggesting that this ratio is insensitive to excitation conditions. In addition, Hubbard and Puetter (1985) find that the Paα/Hα ratio is relatively insensitive to excitation conditions. This assumption finds further support from more recent, unpublished calculations by Puetter (private communication). We therefore believe that the comparison of Paβ and Balmer line intensities is a reasonably robust test for the presence of obscuration and can help identify objects where the intrinsic line ratios are strongly affected by radiative transfer effects. To illustrate, we discuss our observations and other aspects of the individual galaxies.

c) *NGC 2110*

We obtained both low- and high-resoluion spectra of Paβ. They do not show an obvious broad (>800 km s^{-1}) component, with a formal upper limit on the line flux of 2×10^{-14} ergs s^{-1} cm^{-2}. Although radiative transfer effects might be important in a BLR, we expect the line ratios in the narrow-line region (NLR) to follow case B reasonably closely (Koski 1978). Under this assumpton, the reddening toward the NLR, as derived from the Paβ to Hβ line ratio is in close agreement with that from the Balmer decrement, i.e., $A_V \approx 2.3$.

Ward *et al.* (1987*a*) found a proportionality between hard X-ray flux and Hα in a sample of unreddened Seyfert 1 galaxies, with an average of log [F(6 keV)/F(Hα)] = 7. Hard X-ray measurements of NGC 2110 are available from McClintock *et al.* (1978) and Marshall *et al.* (1979). The strength of a broad Paβ component in the galaxy can be estimated assuming

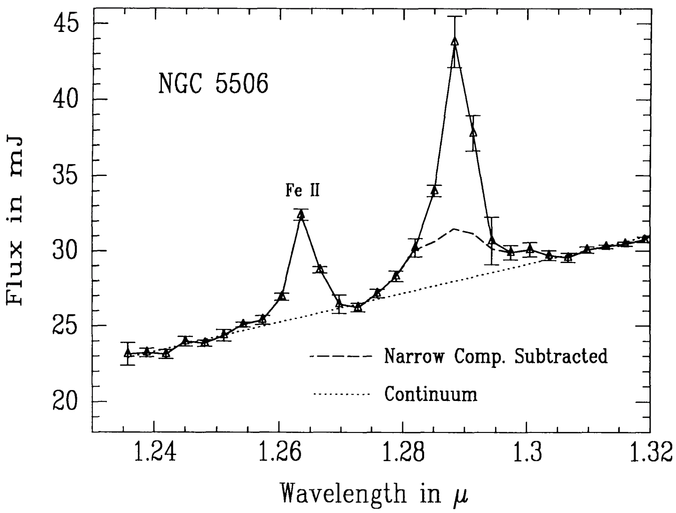

FIG. 1*a*

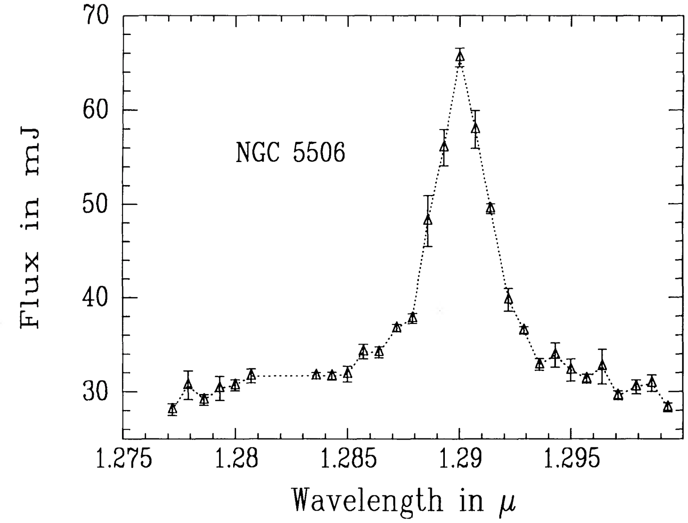

FIG. 1*b*

FIG. 1.—(*a*) Low-resolution spectrum ($R \approx 400$) Paβ spectrum of NGC 5506. We indicate our decomposition of the spectrum into continuum and narrow- and broad-line component. The flux is given in 10^{-3} Jy and the wavelength in microns. The Fe II line (at 1.26 μm rest wavelength) is also indicated. (*b*) High-resolution spectrum ($R \approx 1500$) of NGC 5506 at Paβ. The broad-line component, indicated in (*a*), is spread across virtually the entire spectral range of this spectrum. The narrow component, which is just resolved with this resolution, agrees in strength with the decomposition in (*a*).

that its hard X-ray to Hα ratio is similar to that of unobscured Seyfert 1 galaxies, that the reddening follows a "normal" extinction law (e.g., Rieke and Lebofsky 1985), and that the hydrogen recombination line strengths can be estimated from case B. The result for Paβ is 4×10^{-14} ergs s^{-1} cm^{-2}. This value formally exceeds our upper limit, but not by a sufficient margin that there is a well-established conflict given the other uncertainties and the dispersion in the line strength–X-ray relation. Our data are therefore consistent with the possibility that this galaxy has a normal but obscured Seyfert 1 nucleus, but in this case we predict the detection of a broad recombination line component of a modest improvement in sensitivity.

d) *NGC 2992*

Analyzing the spectrum of NGC 2992 we would like first to understand the flux ratios for the narrow lines. For our present discussion, we take the Balmer line ratios from the high-quality spectra by Ward *et al.* (1980). The absolute flux calibration of these data is inconsistent with the apparently more accurate calibration by Shuder (1980), which is based directly on observations in a 2".7 × 4".1 beam and is therefore comparable with our data through a 6" beam. We therefore adopt the calibration of the latter reference. This choice is supported by the calibration of Durret and Bergeron (1988).

Assuming case B line ratios for the narrow Balmer lines and

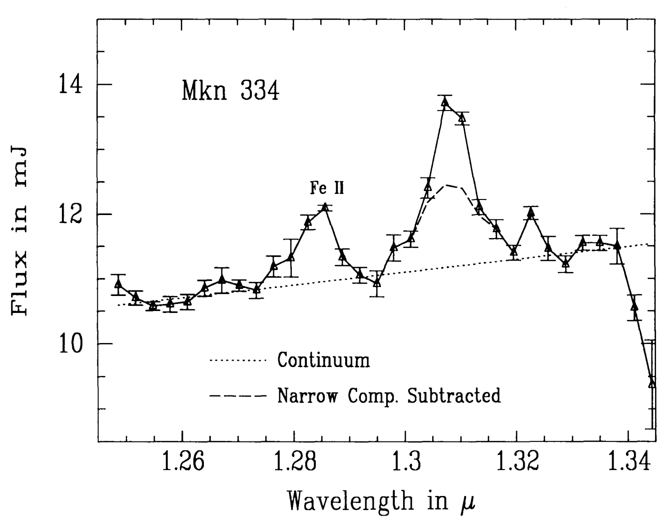

FIG. 2*a*

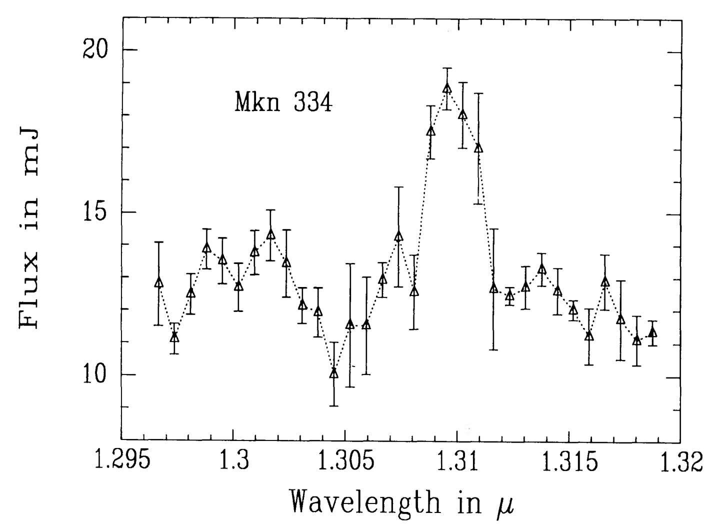

FIG. 2*b*

FIG. 2.—(*a*) Low-resolution Paβ spectrum of Mrk 334. Again, Fe II (1.26 μm) and our line component decomposition are indicated. (*b*) High-resolution spectrum of Mrk 334 at Paβ. The narrow component of the line is clearly visible, while the broad component (see *a*) extends over the whole coverage of the spectrum.

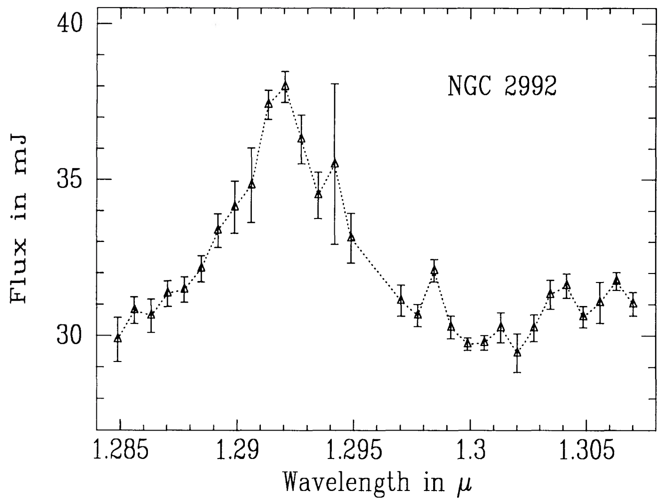

FIG. 3.—High-resolution ($R \approx 1500$) spectrum of NGC 2992 at Paβ. The two-component structure of the line profile is evident, but the narrow component constitutes only a small fraction of the total line flux (contrary to the narrow components of the Balmer lines). Because its relatively small width (FWZI ≈ 2900 km s^{-1}) the broad-line component can be seen in this high-resolution spectrum.

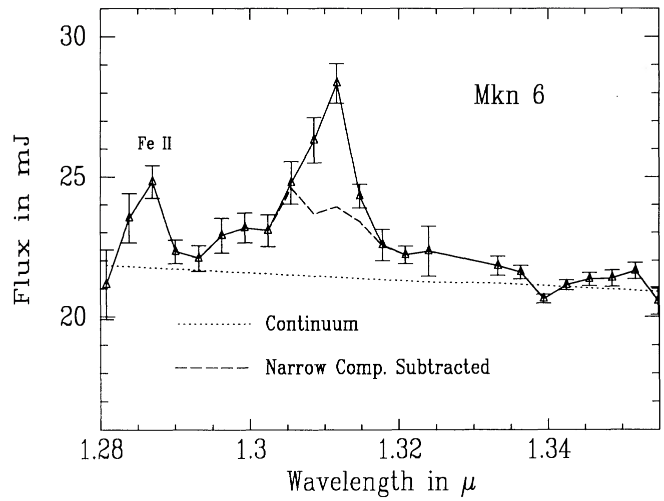

FIG. 4.—Low-resolution Paβ spectrum of Mrk 6. Besides Paβ the Fe II (1.26 μm) line is indicated. The broad component of Paβ is present; however, because of its great width and its low amplitude, its flux cannot be assessed accurately.

a normal reddening law (Rieke and Lebofsky 1985), we find a reddening of $A_V \approx 4.5$ and predict a narrow-line Paβ flux of 12×10^{-14} ergs s^{-1} cm^{-2}. Ward *et al.* (1987*b*) deduce a smaller reddening from the Balmer lines, but recalculating using their equation (1) and the entries in their Table 2 produces a value in close agreement with our estimate.

The line flux predicted above is consistent with the total line flux measurements of 13×10^{-14} ergs s^{-1} cm^{-2} (Ward *et al.* 1987*b*) and 11×10^{-14} ergs s^{-1} cm^{-2} (this work), but our high-resolution spectra show that only ~ 25% of the total line flux is in the narrow component (Fig. 3). We can suggest two possibilities, First, our assmption of case B line ratios might be incorrect. It would be unexpected that radiative transfer effects would significantly affect the line ratios at the densities expected in the NLR. However, the equivalent width of Hβ of 12 Å (Ward *et al.* 1980) is comparable with the maximum equivalent absorption width that can be produced by a hot, young stellar spectrum, 7 Å, (Strömgren 1963), so significant distortion in the Balmer decrement could occur if the nuclear continuum is dominated by such stars. Second, the extinction law may differ substantially from the one we have assumed. Such differences are possible, perhaps even expected, in the vicinity of an active nucleus where the nature of the dust grains may be modified by the extreme environment. Adopting the first of these hypotheses would suggest a reddening over the NLR of $A_V = 2$–3 mag, estimated from the Hα/Paβ ratio. The second possibility would lead to extinction that increased far more rapidly toward the blue than the "normal" law, i.e., an increase in $R = A_V/E_{B-V}$, such as might be produced by a population of small dust grains. This possibility would leave the extinction to the Balmer lines indeterminate.

The uncertainties in extinction complicate the interpretation of the broad-line spectral components. Nonetheless, from the line fluxes in Table 1 and Table 2, we see that the relative fluxes of broad and narrow components increase from 1:1 at Hα to 3:1 at Paβ. In addition, we measured a total P$\alpha\delta$ flux to be 4×10^{-14} ergs s^{-1} cm^{-2}. Estimating the narrow Paδ flux from the optical and P$\alpha\beta$ data, we find that the relative fluxes of broad/narrow are ≈ 2:1. Durret and Bergeron (1988) find the broad/narrow ratio to be 0.9:1 at Hβ and 1.6:1 at Hα in a long slit measurement with a slit width of 2″.

TABLE 1

Paβ FLUXES

Object	Total Flux	Narrow	Broad	Continuum
NGC 2992	10 ± 1	2.4 ± 0.6	8.0 ± 1.8	30 ± 3
NGC 5506	21.4 ± 2.5	12.5 ± 1.5	8.7 ± 2.0	27 ± 3
NGC 2110	1.8 ± 0.6	1.8 ± 0.6	...	34 ± 3
Mrk 6	13.5 ± 2.3	6.4 ± 1.3	7.5 ± 2.3	21 ± 2
Mrk 609	2.4 ± 0.8	...	...	15 ± 2
Mrk 744	10 ± 2	0.55 ± 0.15	9 ± 2.5	20 ± 2
Mrk 334	5.6 ± 0.9	1.7 ± 0.4	4.0 ± 0.8	13 ± 1
Mrk 423	...	0.6 ± 0.3	<2	10 ± 1

NOTES.—The line fluxes are given in units of 10^{-14} ergs s^{-1} cm^{-2}. The continuum is given in mJy.

TABLE 2

BALMER LINE FLUXES

Object	$(H\alpha)_n$	$(H\alpha)_b$	$(H\beta)_n$	$(H\beta)_b$	$(H\gamma)_n$	$(H\gamma)_b$
NGC 2992[a]	27	25	2.1	...	0.4	...
NGC 5506[a,b]	28	12	5.5	...	1.8	...
NGC 2110[a]	20	...	3.4	...	1.1	...
Mrk 6[c]	44	192	9.3	23	3.1	7.8
Mrk 609[d]	8.6	23	1.4	3.0	0.4	...
Mrk 744[e]	12	108	4.5	13	...	...
Mrk 334[f]	16	18	3.2	...	...	...
Mrk 423[g]	3.3	21	0.7	2.1	...	...

NOTES.—The subscripts *n* and *b* refer to the narrow and broad component of the emission lines. Fluxes are given in 10^{-14} ergs s^{-1} cm^{-2}.

[a] From Shuder 1980.

[b] Total Hα flux from Shuder 1980.

[c] Line ratios from Koski 1978, calibration from Yee 1980.

[d] From Rudy *et al.* 1988.

[e] From Goodrich and Osterbrock 1983.

[f] From Dahari 1985.

[g] From Rudy *et al.* 1985.

Decomposition in broad and narrow component: this paper.

Although there are some variations in observational circumstances and probably in methods of deblending the line components, the data show an increasing importance of the broad-line component while going toward longer wavelengths. Particularly given the likely insensitivity of Paβ/Hβ to radiative transfer effects, this result argues that dust absorption is responsible to first order for the unusual observed broad-line ratios and that the extinction is significantly higher over the BLR than over the NLR. Indeed, from our measurements we can make the rough estimate that the extinction toward the BLR is ~ 2 mag greater than that over the NLR, or $A_V \approx 5$.

Once the broad- and narrow-line components have been dereddened by the appropriate amounts, the emission-line properties of NGC 2992 agree well with the ones of "normal" unreddened Seyfert 1 galaxies (or Seyfert 1.5 galaxies). As an additional confirmation, we find that dereddening for $A_V = 5$ reduces the ratio of the hard X-ray flux to the Hα line flux, log [F(6 kev)/F(Hα)], from 224 to 6, in good agreement with the mean value of 7 which Ward *et al.* (1987*a*) found for a sample of unreddened Seyfert galaxies.

e) NGC 5506

Both low- and high-resolution spectra of this object were obtained during three different observing periods, leading to the detection of a broad (FWHM $\approx$ 2800 km s^{-1}) component of the Paβ line (see Fig. 1*a*). This measurement shows the existence of a—previously suspected—BLR. One of us (N. P. C.) obtained a very high S/N spectrum between Hβ and Hα which shows a weak broad Hα component, which constitutes $\sim 25\%$ of the total flux.

The strength of the narrow component of Paβ (see Fig. 1*b*) confirms the NLR extinction estimates derived from the Balmer lines, yielding $A_V \approx 3.3$ mag. The relative strengths of broad- and narrow-line components then suggest that there is additional obscuration toward the BLR of $A_V = 1$–2 mag. Although this quantitative extinction estimate is based on case B line ratios, it seems almost certain that dust obscuration of the BLR is primarily responsible for the deviation of the line ratios from those in other Seyfert galaxies, since most model calculations predict Hα to be enhanced with respect to the high level lines relative to the case B predictions.

This interpretation is not in conflict with the nondetection of a broad Brγ component (Moorwood 1989). The equivalent width of any broad Brγ component can be predicted from our Paβ measurements: if we assume one additional magnitude of visual extinction toward the BLR, then the broad and the narrow component of Brγ are expected to have the same equivalent width. However, because of its much greater width the peak amplitude of the broad line would be only 20% of that of the narrow component. Thus Moorwood's (1989) spectra, in which the narrow Brγ line is detected, do not seem to impose a stringent limit on the broad component.

Accepting the hypothesis of dust obscuration of the BLR, we estimated the dereddened strength of the broad Hα line from the measured Paβ strength (assuming an extinction of $A_V = 5$ mag). As with NGC 2992, this dereddened line flux again fits the log [F(6 keV)/F(Hα)] relation determined for unreddened Seyfert 1 galaxies.

f) Mrk 334

Dahari (1985) published an optical spectrum of this object and classified it as a Seyfert 1.8 galaxy. The narrow components of Hβ (see Fig. 2*b*), Hα and Paβ, yield a consistent picture, assuming $A_v \approx 1$ mag toward the NLR. While for Hα the ratio of broad to narrow flux is unity, for Paβ the broad component is more than twice as strong as the narrow one (see Fig. 2*a*). As in NGC 2992 and NGC 5506, again we find an increase of the broad component compared to the narrow one, arguing for dust reddening as the cause of the weak broad lines. Assuming standard intrinsic line strengths for Hα and Paβ, we find an additional 1–1.5 mag of extinction toward the BLR. A hard X-ray detection of this galaxy was extracted from the *HEAO A-1* data base as described by Rieke (1988). Comparing the dereddened Hα flux to the hard X-ray emission ($800 \pm 200 \times 10^{-14}$ ergs s^{-1} cm^{-2}) yields a ratio of 9, again in agreement with the value found for nearby unobscured AGNs.

g) Mrk 6

On three different observing runs, we obtained high- and low-resolution spectra of Paβ which allowed a separation of the two line components (one of these spectra is shown in Fig. 4). The strength of the narrow component confirms the estimate from the Balmer lines of the extinction toward the NLR: $A_V = 2$ mag. However, the observed steep Balmer decrement for the broad component (Koski 1978) cannot be explained by dust reddening. For example, for Hα the broad component is 4 times as strong as the narrow one (Koski 1978), whereas for Paβ, the two components are of almost equal strength. From reddening, we expect just the opposite behavior, as seen in NGC 2992, NGC 5506, and Mrk 334. This argument might be weakened by the variability of the broad lines (McAlary *et al.* 1986) and our lack of an optical spectrum simultaneous with the infrared observations. However, if we assume that the Balmer decrement is constant and use measurements of broad Hβ to estimate the broad Hα line flux, the same problem persists at the weakest level of broad line flux observed (McAlary *et al.* 1986).

This result is consistent with the previous (low-resolution) measurements of Brγ, Paα, and Paβ by McAlary *et al.* (1986), who did obtain nearly simultaneous optical data. Their measurement of the total Paβ flux agrees well with ours, so we can ignore BLR variability in our comparison. Using the available narrow-line fluxes (including Paβ) and assuming that they obey case B with an extinction of 2 mag, we can predict the narrow line Paα and Brγ fluxes and compare them with the integrated line intensities observed by McAlary *et al.* In both cases, the narrow lines account for about two-thirds of the total line flux, whereas for Hβ McAlary *et al.* found that the narrow line accounted for less than half the total line flux. Again we conclude, in contradiction with the hypothetical presence of substantial extinction, that the relative importance of the broad line components do not increase toward longer wavelengths. Our work therefore confirms the conclusion of McAlary *et al.* (1986).

These results suggest that the extinction toward the BLR in this galaxy is no more, and quite probably less, than that to the NLR. If we are looking at Mrk 6 nearly along the axis of the central source pattern, and if peripheral matter (e.g., dust and low-density gas clouds) is swept out along this axis, a clear view to the innermost regions might result. If the narrow-line material is located in a quasi-toroidal region around the axis, we may except that there will be some dust associated with it. High-resolution images of NGC 4151 and NGC 1068 (Ebstein, Carleton, and Papaliolios 1989) show that the narrow-line emission is extended bidirectionally along the radio axis, but appears to lie on either side of the axis itself. If the motion of the gas is radial, then we might expect to see large velocities in Mrk 6 if we are looking along the axis, and indeed the [O III] λ5007 line has very broad wings (Vrtilek and Carleton 1985).

h) *Mrk 744*

The optical spectrum of this Seyfert 1.8 galaxy was originally discussed by Goodrich and Osterbrock (1983). These authors found that there is no evidence for reddening toward the NLR, which is confirmed by our measurement of the narrow Paβ component. The flux of the broad Paβ is just what one expects from standard line ratios (without reddening) when compared to Hβ but is much too weak when compared to Hα. This strongly argues against dust reddening as the cause of the steep Balmer decrement of 8.4, but rather indicates that radiative transfer effects enhance Hα. Thus Mrk 744 appears to be a case similar to Mrk 6.

i) *Mrk 609*

For this object, originally classified as a Seyfert 1.8 galaxy (Osterbrock 1981), we measured a total Paβ flux of 2.4×10^{-14} ergs s^{-1} cm^{-2}, but we were not able to decompose the line flux unambiguously into narrow and broad components.

From the published optical spectra (Rudy, Cohen, and Ake 1988) it seems possible that the measured Balmer decrement is substantially afflicted by the underlying absorption of the stellar component. However, if we assume that most of the Paβ flux arises from a narrow component, then Paβ, together with the narrow Balmer lines (Rudy *et al.* 1988; Osterbrock 1981), is well fitted with case B line ratios and a reddening of $A_V \approx 3$ mag for the NLR.

This result is quite remarkable in the light of the convincing argument by Rudy *et al.* (1988) that the reddening for the BL and the nonstellar continuum must be small. Assuming case B ratios, they found $A_V = 0.3$ from the Lyα/Hβ ratio. Even extreme models to maximize the intrinsic value of this ratio (Rudy, Cohen, and Ake 1988) were found to demand $A_V < 1$ mag. Similarly, unless the continuum is assumed to be bluer than any other known AGN, it is required than $A_V < 0.3$ mag. Thus, we must conclude that Mrk 609 is another case like Mrk 6, where the NLR is more affected by reddening than the BLR and continuum source and the steep and variable Balmer decrement in the BLR is strongly influenced by radiative transfer effects (Osterbrock 1981; Rudy, Cohen, and Ake 1988).

j) *Mrk 423*

Rudy, Cohen, and Puetter (1985) concluded from the absence of a broad Lyα component that reddening must be at least partly responsible for the steep Balmer decrement in the broad lines of this Seyfert 1.9 galaxy. They estimate extinction values for the BLR of $1.1 < A_V < 3.4$. Our nondetection of a broad Paβ component is consistent with this picture; however, the upper limit on the Paβ/Hβ ratio implies $A_V < 2.3$ mag. The extreme line width (FWZI $\approx$ 20,000 km s^{-1}) of the broad components, which is of the order of the spectral coverage of our spectrometer for a single grating setting (in low-resolution mode), complicates the definition of the continuum and does not allow us to set more stringent limits on the broad Paβ component without obtaining higher quality data. Rudy, Cohen, and Puetter (1985) suggest that the extinction to the NLR and stellar continuum is less ($A_V < 0.9$) than that to the BLR. Our limit on the narrow Paβ is not sensitive enough to provide an independent test of this possibility.

IV. DISCUSSION OF OVERALL BEHAVIOR

As it has been discussed extensively in the literature (see, e.g., MacAlpine 1985) there are three main reasons for the hydrogen line ratios to deviate from "canonical" case B values: First, high density and radiative transfer effects in the emitting gas can cause very substantial changes in the *intrinsic* line flux ratios. Second, underlying stellar absorption features can change the *measured* line ratios. Third, dust reddening can drastically alter the observed line fluxes, in the sense of suppressing the lines at shorter wavelengths compared to the "redder" lines.

In our sample of eight AGNs, which was selected on the basis of exceptionally steep Balmer decrements, we found all three effects to be present. We found that Paβ spectroscopy is an effective tool to untangle these various alternatives: We were able to show (or, in some cases, confirm) (1) that the intrinsic Balmer decrement is steep for Mrk 6, Mrk 744 and Mrk 609, (2) that the underlying stellar spectrum is important (NGC 2992 and Mrk 609) and (3) that substantial dust obscuration, in particular of the BLR, is present (in NGC 2110, NGC 2992, NGC 5506, Mrk 334, and Mrk 423).

We find that the broad line ratios for Mrk 6, Mrk 744 and Mrk 609 are well within the range predicted by Hubbard and Puetter (1985), if Paβ is affected similarly to Paα (Avrett and Loesser 1988). However, any quantitative discussion of these line ratios is severely hampered by the fact that hardly any theoretical models include Paβ. Therefore we restrict ourselves for now to a plea for inclusion of the Paβ flux in BLR models, since we have demonstrated that it can be measured with high resolution ($\approx$1500) at the flux levels of interest ($\approx 10^{-14}$ ergs s^{-1} cm^{-2}). In the remainder of this section we will concentrate on the role of dust in these AGNs.

For the four (possibly five) cases for which we find dust obscuration to be present, the dereddened line strengths show these objects to agree well in their broad-line properties with Seyfert 1 galaxies (or Seyfert 1.5 galaxies).

Let us consider four cases for the distribution of the dust that obscures the broad-line regions in galaxies such as NGC 2992, NGC 5506, and Mrk 334: (1) The obscuring dust lies in the plane of the galaxy well in front of the nucleus. (2) It is distributed in the extension of the disk into the bulge around the nuclear region, similar to the material in Sgr A, B, and C in the Milky Way. (3) The dust is distributed throughout the region very close to the active nucleus. (4) It is in a ring structure (similar to the 4 pc diameter molecular ring around the Galactic center) around the active nucleus. Three observational constraints are useful in testing these models: (1) the measured optical and infrared hydrogen recombination line strengths; (2) the spectral energy distributions of the galaxies; and (3) statistical arguments regarding the prevalence of Seyfert galaxies with broad-line regions.

The first class of model may be difficult to reconcile with statistical considerations. The covering factor for the obscuring dust can be estimated by noting that Ward *et al.* (1988) find from a complete sample of 34 hard X-ray Seyfert galaxies that four (NGC 2992, 5506, 7413, and 7582) have characteristics suggestive of very heavy reddening of the BLR. Here and below, we will assume from these statistics that $\sim$10% of the sky as viewed from the nucleus is covered by heavily obscuring dust. A typical scale height for dust in galactic planes can be estimated to be less than 100 pc, both from the *IRAS* images of the Milky Way (Hauser *et al.* 1984) and from 2 μm images of external galaxies (unpublished data). The axial ratios of these four galaxies are 2.5–3.5, indicating inclinations of no more than 65°–75°. An inclination of 70° and scale height of 100 pc would place the obscuring dust clouds within $\approx$0.5 kpc of the nucleus, well inside the plane of the galaxy.

The second class of model is clearly compatible with these statistics, since the radial scale of 0.5 kpc derived above is an appropriate one for circumnuclear clouds. In this model, variations in the amount of dust overlying different parts of the nucleus from our vantage point are responsible for the observed variations in extinction. A simple form of such models would have the narrow-line region lie behind two zones, the first with moderate and the second with heavy extinction. The nucleus would lie behind the second zone.

Such models can be tested under the assumption that there are case B hydrogen recombination line ratios in the NLR. A specific model of this type for NGC 5506 would have extinctions of $A_V = 2.65$ over half the NLR and $A_V = 5$ over the BLR and remaining NLR. This model provides an excellent fit to the observed narrow-line ratios shown in Tables 1 and 2. Given the free parameters afforded by more complex versions of this class of model, it is likely to remain consistent with much more complete line strength measurements.

An extension of this model would also be consistent with the observations of Mrk 6, which is viewed more nearly face on. Here the NLR seems to be affected by dust but the BLR less so. Since this model predicts a dust distribution concentrated in the disk of the galaxy, it seems plausible that we can get an unobscured view of the central region in more face on objects (Mrk 6, Mrk 744, and Mrk 609).

In the third class of model, the additional reddening of the BLR arises in clouds of dust that lie around the BLR inside the NLR. We would associated this dust with the hot thermal source component that typically dominates the spectra of type 1 Seyfert galaxies near 3.5 μm (e.g., Lebofsky and Rieke 1979; Carleton *et al.* 1987; McAlary and Rieke 1988). However, this type of model would require that heavily obscured BLRs should be found in a significant subset of reasonably face on Seyfert 1 galaxies. However, for all known face on galaxies with steep Balmer decrements (NGC 1275, Mrk 231, VZw 317, Mrk 6, Mrk 744, and Mrk 609), the decrements appear to arise from radiative transfer effects, not obscuration. In this class of model, it is also difficult to account for the behavior of Mrk 6, where the BLR is subject to less obscuration than the NLR.

The fourth model avoids the difficulty in the preceding case by localizing the circumnuclear dust. However, it should be kept in mind that the molecular ring in the Galactic center is tilted significantly out of the plane of the galaxy, by $\sim$25° to our line of sight (Genzel 1989); hence, there would be little expectation that the behavior of these galaxies would be strongly correlated with their inclinations, and in some cases one would expect to find heavily dust-obscured BLRs in moderately face-on galaxies. Mrk 334 ($i = 40°$) might provide such an example; it would be useful to search for other galaxies similar to it.

Thus, for the dust reddened AGNs, the most likely location of the dust is in the circumnuclear region but perhaps not particularly close to the active nucleus, corresponding to the second model proposed above.

V. CONCLUSIONS

The main conclusions of this work can be summarized as follows:

1. We have demonstrated the feasibility of high-resolution Paβ spectroscopy for a sample of intermediate Seyfert galaxies and have shown the usefulness of these measurements to test whether dust obscuration is the main reason for the unusual Balmer line ratios observed in these objects.

2. A detailed analysis of line ratios including Paβ is difficult, because this line is not explicitly included (or published) in most theoretical models. We argue the inclusion of Paβ in all models of BLRs published in the future.

3. In our sample of intermediate Seyfert galaxies with steep Balmer decrements we found three types of behavior to be present: (a) The Balmer decrement is intrinsically steep due to high gas densities or radiative transfer effects; dust obscuration does not play an important role. (b) The hydrogen line ratios of the broad components can be explained by additional reddening between the NLR and the BLR. (c) It is possible that the NLR is more heavily obscured than the BLR.

4. The frequency and strength of dust obscuration in Seyfert galaxies can be best explained by assuming a circumnuclear dust distribution very similar to the one found in our own galaxy.

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Note added in manuscript.—The results presented in this paper are roughly consistent with Paβ flux measurements at a substantially lower spectral resolution obtained independently for some of the objects by Goodrich (1990) and Blanco, Ward, and Wright (1990). In the cases where there is some disagreement, this can be attributed to the lower resolution and sensitivity of their measurements.

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N. P. Carleton: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

Marcia Rieke, George Rieke, and Hans-Walter Rix: Steward Observatory, University of Arizona, Tucson, AZ 85721