1992ApJ...393..658M

THE ASTROPHYSICAL JOURNAL, 393:658–665, 1992 July 10

TWIN PEAKS: IC 4329A AND ARAKELIAN 120[1]

P. MARZIANI
International School for Advanced Studies, Strada Costiera 11, I-34014 Trieste, Italy
M. CALVANI
Osservatorio Astronomico di Padova, Vicolo Osservatorio 5, I-35122 Padova, Italy
AND
J. W. SULENTIC
Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487
Received 1991 July 24; accepted 1992 January 16

ABSTRACT

New spectrophotometric observations of the Seyfert 1 galaxies IC 4329A and Arakelian 120 are presented. The low-ionization broad emission lines (as evidenced by Hβ) are strikingly similar. The so-called zero peak in the Balmer lines of these objects appears to be both broader than and blueshifted relative to the [O III] $\lambda\lambda$4959, 5007 lines. It is apparently not a narrow-line component. We confirm that the Balmer line profiles in IC 4329A are variable in shape, and we demonstrate that the profile variations are very similar to those seen in Akn 120. This similarity has important implications for models of the central engine and line-emitting regions of AGNs: (1) it implies that some kind of ordered and reproducible motion is taking place in the broad-line region (BLR) and (2) it argues against models explaining the central source of AGNs in terms of separate accretors or supernova events. Profile variability and energy balance considerations argue against the hypothesis that the lines are emitted by an accretion disk. Further clues to the nature of these objects and to the structure of the central engine of AGNs are discussed.

Subject headings: galaxies: individual (IC 4329A, Akn 120) — galaxies: Seyfert — line: profiles

1. INTRODUCTION

In the past few years attention has been given to the idea that an accretion disk around a supermassive black hole could be responsible for the broad Balmer line emission in some Seyfert 1 and broad-line radio galaxies (BLRGs). The outer regions of hypothesized disks are probably at a distance of $d \sim 1$ lt-month from the central source, as estimated from the broad-line region (BLR). The theoretical work of Dumont & Collin-Souffrin (1990a, b, c) also suggests that the outer regions of the disk are at conditions suitable for the emission of the low-ionization lines (LILs: H I Balmer lines, Fe II, and maybe Mg II λ2798). The Balmer line profiles of Arp 102B (Chen, Halpern, & Filippenko 1989) and 3C 332 (Halpern 1990) are a good match to models where the emission originates from an accretion disk for which relativistic effects are nonnegligible. Analysis of the profile variations in Arakelian 120 (Alloin, Boisson, & Pelat 1988), NGC 5548, and NGC 3783 (Stirpe, de Bruyn, & van Groningen 1988) suggest that the BLR in these galaxies is made up of at least two parts, one of which emits a double-peaked contribution to the Balmer lines, as expected from a disklike structure. It is not clear whether the same considerations can be applied to other objects, since the expected profiles of lines emitted by a rotating disk cannot readily explain the generality of observed profile shifts and asymmetries (Sulentic et al. 1990). Seyfert 1 galaxies and BLRGs are good prospects for finding further candidates for line-emitting disks. We are carrying out a spectroscopic survey of these objects especially when they show irregular and very broad Balmer line profiles. This survey has a twofold utility since:

1. Analysis of the profiles and profile variations may be useful for understanding gas kinematics in the BLR (although it is generally suggested that radial motions are dominant, it is yet unclear whether infall or outflow is taking place);
2. They could provide additional support for and, possibly, constraints on models for the central source in AGNs. The most widely accepted model (i.e., accretion in a disk around a supermassive black hole) has observational support mainly limited to the existence of the so-called big blue bump (Malkan & Sargent 1982; for a recent review see Ulrich 1991).

General results on the entire observed sample of Seyfert 1 and BLRGs will be presented elsewhere (Marziani et al. 1992). In this paper, we present new results for the Seyfert 1 galaxy IC 4329A and a comparison with Akn 120 which has very similar BLR properties. Although IC 4329A is a bright and nearby Seyfert galaxy, absolute optical spectrophotometry has only recently been published (Morris & Ward 1988; Fricke & Kollatschny 1989). Spectra were also published by Wilson & Penston (1979). The latter authors did not present spectrophotometry, but pointed out that variations in the emission-line fluxes were plausible. This suggestion was later confirmed by Morris & Ward (1988).

We confirm the existence of variations in the Balmer line profiles. We demonstrate that the variations, analyzed using new spectrophotometric data and previously published spectra, are very similar to those seen in the well-studied Seyfert 1 galaxy Akn 120. Spectral variability in Akn 120 was first noted by de Bruyn (1980) and Schulz & Rafanelli (1981). Unlike IC 4329A, Akn 120 has been extensively studied in the optical by several authors (e.g., Peterson et al. 1983; Alloin et al. 1988). The importance of studying objects with very similar line profiles stems from the possibility that they have similar kinematics/geometry/orientation to the line of sight. Detailed

---

[1] Based on observations collected at ESO-La Silla.

study may lead to the discovery of other similarities (or differences) in key parameters related to the physical conditions in the BLR. It could provide a starting point in the search for global correlations between various AGN parameters and profile classes. Consequences and constraints on the BLR structure and central source models resulting from our comparison of Akn 120 and IC 4329A are discussed in the last section of the paper.

2. OBSERVATIONS AND DATA REDUCTION

IC 4329A (1346−3003) and Akn 120 (0513−0012) were observed during the period 1–4 1990 April with the 1.52 m ESO telescope at La Silla. It was equipped with a Boller and Chivens spectrograph and a high-resolution (pixel size 15 μm × 15 μm) RCA CCD detector. The slit width employed was ≈2″ during all four nights of observation. All observing nights were photometric with seeing estimated to be ≲1″. The dispersion used on April 1 and 2 was 67 Å mm^{-1}, allowing a spectral resolution of ≈1.8 Å FWHM. The spectral ranges covered were 6400–7400 Å on April 1 and 4650–5550 Å on April 2. The dispersion was set to 120 Å mm^{-1} on April 3 and 4, yielding a spectral resolution of ≈3.5 Å FWHM. Recorded spectral ranges were 5440–7380 Å on April 3 and 3550–5450 Å on April 4. Spectra were bias subtracted, flat-field corrected, and wavelength calibrated using a third-order polynomial on unblended emission lines from a HeAr comparison source recorded after each observation. The rms was always less than 0.1 Å. Flux calibration was obtained from three or four nightly observations of a standard star from the list of Stone (1977). A standard star spectrum was obtained before or after the spectra of IC 4329A and Akn 120, with a slit width of 10″. Note that a larger slit width was needed in order to measure the brighter standard stars. We believe that this process allows us to obtain accurate absolute fluxes for our sources. The photometric quality of the nights and the good seeing conditions permitted fluxes to be measured with an accuracy of ±15%.

3. RESULTS

3.1. *Line Profiles*

The profiles of Hβ and Hα are shown in Figures 1*a* and 1*b* for IC 4329A and Figures 1*c* and 1*d* for Akn 120, respectively. They have very similar shapes, and the profiles would be classified as type SR (red-displaced, symmetric profile) in the scheme proposed by Sulentic (1989). Neither object was included in that study of Hβ profile shape and asymmetry that included 61 AGNs. A more descriptive type might be AB, R (red asymmetric profile with blueshifted peak), but neither the blueshifted peak nor the red asymmetry of the base are strong enough to affect a classification based upon measures at three-quarter, one-half, and one-quarter intensity. The peculiar structure is concentrated in the upper and lower one-quarter of the profile. The SR designation is therefore independent of assumptions about the narrow- or broad-line origin of the profile peak. SR profiles are quite common, while AB, R profiles were found to be rare in the Sulentic (1989) study with only one AGN (I Zw 1) assigned that type. Perhaps an extension of the classification scheme is needed in order to quantify peculiarities of the kind found in Akn 120 and IC 4329A. This would be appropriate when larger samples of (Fe II decontaminated) spectra with sufficient resolution and S/N become available. We are restricted for the present to comparisons of the kind presented in this paper.

Emission-line fluxes are presented for IC 4329A and Akn 120 in Table 1. The bottom rows give the heliocentric redshift, the observed Hβ luminosity, the reddening $E(B-V)$, and the reddening-corrected Hβ luminosity. The reddening $E(B-V)$ was first computed from the ratio of Hα and Hβ fluxes, assuming the case B recombination value. This is probably not appropriate for the BLR. Collisional and radiative transfer effects at BLR densities (10^{10}–10^{12} cm^{-3}) are strongly dependent on the exact density value, leading at first to an increase of the Hα/Hβ ratio and then to a decrease for $n_e \gtrsim 10^{11}$ cm^{-3}. If we assume that the Balmer decrement observed for Akn 120 is appropriate for the BLR, and that it is reddening free, then a reddening value of $E(B-V) \approx 0.8$ is obtained for IC 4329A. This is in good agreement with the reddening value deduced from the equivalent hydrogen column density needed to reproduce the low-energy absorption in the X-ray spectrum (Singh, Rao, & Vahia 1991). Both values of $E(B-V)$ are reported in Table 1.

The profile similarity between Akn 120 and IC 4329A is very striking, with Hα and Hβ in the two galaxies having nearly identical FWHM ≈ 6000 km s^{-1}. The FWZI values for Hα are ≈30,000 km s^{-1} for IC 4329A and 26,000 km s^{-1} for Akn 120. For Hβ the FWZI values are 22,000 km s^{-1} for both objects. The FWZI values of Hβ and Hα are large even for Seyfert 1 galaxies (cf. Padovani & Rafanelli 1988). No general trend in profile shape was found among the very broad profile objects included in the Sulentic (1989) study. A weak blue wing is detected (in IC 4329A) out to −18,000 km s^{-1} in Hα (its detection in Hβ is hampered by the presence of Fe II and He II λ4686 lines on the blue side of that profile). The Hβ profiles

TABLE 1

EMISSION-LINE MEASURES

Line Identification		IC 4329a		Akn 120	
		Flux[a]	EW (Å)	Flux[a]	EW (Å)
[S II]	λ6731	0.23	...	0.086	...
[S II]	λ6717	0.19	...	0.098	...
Hα[b]	λ6563	32.6	515	35.5	519
[O I]	λ6300	0.072	...	0.12	...
[Fe VII]	λ6087	0.06	...	...	...
He I	λ5876	1.81	...	...	
[Fe VII]	λ5721	0.145	2.5	...	...
Fe II blends	λ5250[c]	1.20	25	3.12	41
[O III]	λ5007	1.33	...	0.66	...
[O III]	λ4959	0.42	...	0.22	...
Hβ	λ4861	3.68	90	10.5	118
Fe II blends	λ4570[d]	0.73	22	3.43	34
[O II]	λ4363	0.28	...	0.42	...
Hγ	λ4340	0.25	...	3.52	...
Hδ	λ4101	...	...	1.44:	...
z	...	0.0159 ± 0.0001		0.0324 ± 0.0001	
$L_{\mathrm{H}\beta}$	(ergs s^{-1})	1.0×10^{41}		1.2×10^{42}	
$E(B-V)$[e]	...	0.98		0.16	
$E(B-V)$[f]	...	0.8		...	
$L_{\mathrm{H}\beta,\ \mathrm{redd.\ corr.}}$	(ergs s^{-1})[g]	2.4×10^{42}		2.0×10^{42}	

[a] Fluxes are in units of 10^{-13} ergs s^{-1} cm^{-2}.

[b] Hα broad and narrow component, and [N II] λλ6548, 6583.

[c] Fe II blends measured from 5190 to 5320 Å.

[d] Fe II blends measured from 4460 to 4700 Å.

[e] Estimated from the radio Hα/Hβ, assuming case B Balmer decrement.

[f] Estimated from the radio Hα/Hβ, assuming as the intrinsic Hα/Hβ ratio that of Akn 120.

[g] Using $E(B-V)$ computed for case B Balmer decrement.

1992ApJ...393..658M

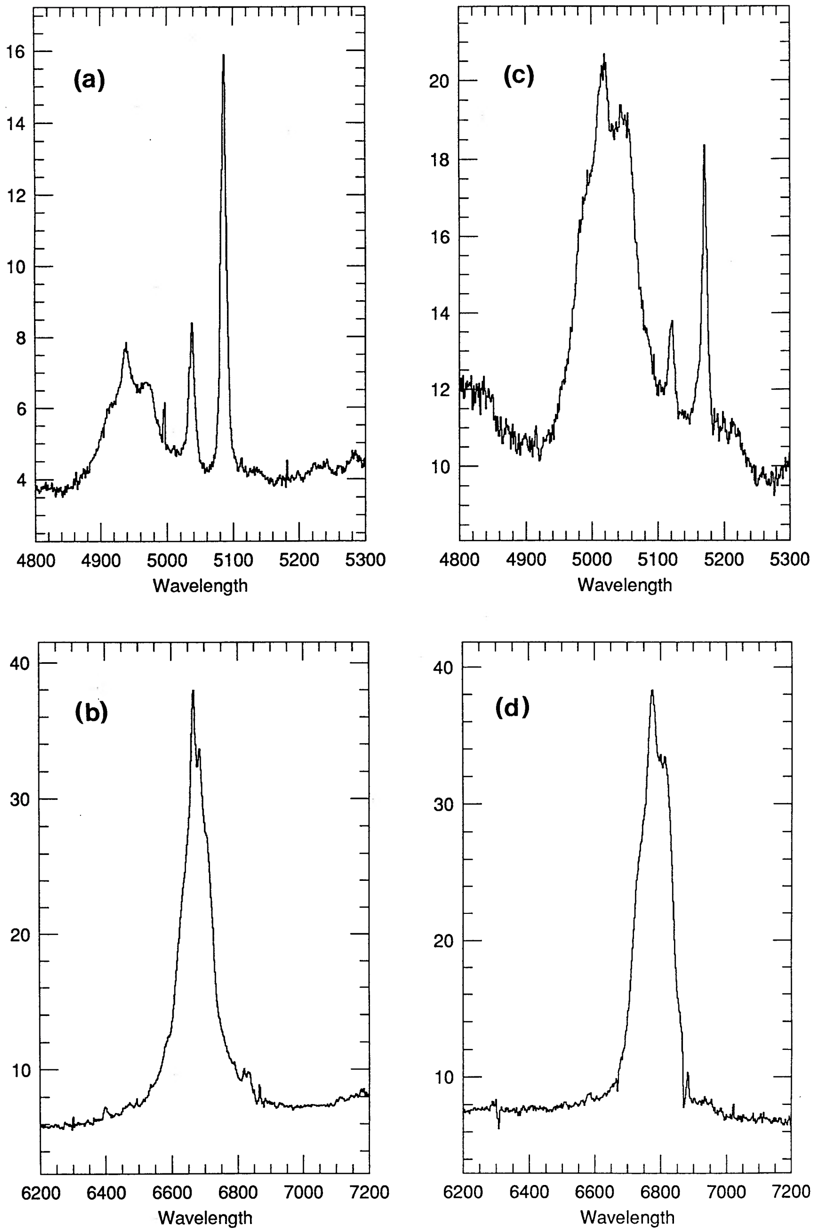

FIG. 1.—Line profiles of IC 4329A: (*a*) Hβ and (*b*) Hα, and of Akn 120: (*c*) Hβ and (*d*) Hα. Vertical scale of flux (10^{-15} ergs s^{-1} cm^{-2}); horizontal scale is wavelength in Å.

clearly show two peaks: (1) a peak or shoulder displaced to the red by ~ 1800 km s^{-1} (hereafter the "red" peak) and (2) a peak near the redshift of the narrow lines (hereafter the "zero" peak).

We suspect a small ($\Delta V_r = 50$ km s^{-1}) blueshift of the zero peak in Hβ relative to the [O III] $\lambda\lambda$4959, 5007 lines for IC 4329a (a similar value was derived at a low level of confidence by Wilson & Penston [1979]). The NLR redshift is assumed to be the same as the systemic velocity of the host galaxy derived from absorption-line measures. Akn 120 shows a much larger ($\Delta V_r = 300$ km s^{-1}) blueshift of this feature. The zero peak of Hβ appears distinctly broader than the [O III] $\lambda\lambda$4959, 5007 lines ($\gtrsim 15$ Å compared to ~ 7 Å at the same fractional intensity), both for Akn 120 and IC 4329A. The greater width of the zero peak and its radial velocity displacement suggests that it is another BLR component rather than an NLR contribution as has often been assumed. The case is stronger for Akn 120, but the overall similarity of the profiles argues in favor of a common interpretation. The object OX 169 may represent a third example of the profile class considered in this paper. Measures by Marziani (1991) show a red peak ($+1400$ km s^{-1}) and a slighly blueshifted (-300 km s^{-1}) zero peak. Stockton & Farnham (1991) have treated the zero peak in this object as a BLR rather than an NLR feature. The situation for Hα in Akn 120 and IC 4329A is more confused (due to [N II] $\lambda\lambda$6548, 6583 emission), but the same general structure appears to be present.

In the past there was some confusion about the identification of the peaks. The Hβ profile of Akn 120 has even been described as double-peaked (Foltz et al. 1981) with displaced red *and* blue components. A blue peak was possibly seen only in one spectrum. The low S/N ratio of this spectrum, lack of confirmatory data, and width of the feature make this detection suspect. The so-called blue peak has instead been observed by us and by several others as an inflection on the Hβ profile.

3.2. *Emission-Line Variability*

A comparison with the spectra published by Wilson & Penston (1979) and with the fluxes published by Morris & Ward (1988) and Fricke & Kollatschny (1989) suggests that the Balmer lines in IC 4329A go through a high- and low-luminosity phase. Broad-line fluxes (Hα and Hβ) decreased in the period of time from 1975 June to 1977, June, but they increased again in 1984, when IC 4329A was observed by Fricke & Kollatschny (1989). The observations of Morris & Ward (1988) suggest that in 1985 the object was in the high phase, but probably fading. Fluxes were considerably lower in 1990, when our observations were made. Hence, at that time IC 4329A was near to the low phase. Peterson et al. (1983) and Alloin et al. (1988) previously suggested that it was appropriate to consider a *low*- and a *high*-luminosity phase for Akn 120. The Hβ flux of Akn 120 changes by a factor of ≈ 2–3 on a time scale of several months to 1 year, in response to changes in the continuum.

The general shape of the Hβ profile does not change significantly as measured by the half-width at different intensity levels or by the asymmetry index. If one compresses the bright phase spectrum to the same scale as the low-phase one, the profile similarity remains remarkable even between the two objects. The tendency for profiles to preserve the same shape during variation was noted in Sulentic (1989). The *details* of the Hβ profile in Akn 120 show changes. A high S/N spectrum published by Foltz, Wilkes, & Peterson (1983), for example, shows that the red peak is almost as strong as the zero peak. These changes would not show up in a coarse profile classification scheme. While the zero and red peak in Hβ do have comparable intensities at some epochs, the red peak has always (in all published spectra) been less prominent in the Hα line suggesting that the Balmer decrement is less steep for the component emitting the red peak. This possibility was considered earlier by Osterbrock & Phillips (1977).

Fe II lines vary appreciably in response to continuum variations, following the same behavior as the Balmer lines. Although Fe II lines may enhance the red wing and peak of the Hβ profile, they are unlikely to be responsible for all of the emission from these features. In particular, emission from multiplets 36 and 42 in such broad-line objects would not be able to completely account for the red peak. Both the red wing and peak persist when Fe II diminishes greatly in strength. This can be seen in the spectra published by Wilson & Penston (1979) as well as in our data (the relevant spectral region is only partially displayed in Fig. 1). The Fe II emission is considerably stronger in Akn 120 than in IC 4329A. The difference in strength of the Fe II features, along with morphology of the host galaxies, are the most prominent *differences* between the two objects: the ratio Fe II(λ5250)/Hβ is $\lesssim 0.20$ for IC 4329A and ≈ 0.33 for Akn 120. Foltz et al. (1983) argue that a broad [O III] $\lambda\lambda$4959, 5007 forbidden line component may also contribute to the red wing.

The difference spectrum of Hα between the low- and high-luminosity phase in Akn 120 shows a double-peaked profile, whose peaks are shifted by ± 2000 km s^{-1} with respect to the radial velocity of the zero peak (Alloin et al. 1988). We have repeated the same operation on the Hβ and Hα profiles of IC 4329A, taking as representative for the high state the spectrum of 1975 June published by Wilson & Penston (1979). We have been able to produce similar structure in the IC 4329A profile using the [O III] $\lambda\lambda$4959, 5007 lines as a fixed intensity reference. The peaks are shifted by $\pm 1950 \pm 100$ km s^{-1} with respect to the systemic velocity of IC 4329A. In both cases, the blue peak of the difference spectrum appears as a shoulder on the blue side of Hβ, while the red peak of the difference spectrum corresponds to the red peak of the observed profile. The difference spectrum for OX 169 (Stockton & Farnham 1991) shows only a single (red) peak.

The difference spectrum published by Alloin et al. (1988) for Akn 120 is the strongest evidence for an underlying double-peak (disk-related) component in the Balmer lines. Unfortunately a convincing double-peak structure is only seen in the Hα profile. This raises questions about the reality of a distinct double-peak component. Hβ is a cleaner feature for generating a difference spectrum, and our observations, as well as the difference spectrum published by Alloin et al. (1988), suggest that it retained the same general shape during the variations. The double structure should be more distinct at Hβ especially if the Balmer decrement in the red component is flatter than for the central emission. Hα is confused by the presence of the narrow [N II] emission features and the zero peak. Since the difference spectrum was produced from data taken with different equipment, small differences in resolution could affect the width of the narrow emission components. In addition, if the two spectra were slightly mismatched in wavelength at Hα, a further error in the subtraction might result. It is very difficult to prove that only the shoulders of the Balmer lines are varying in these objects. This is especially true because of the zero peak. As mentioned earlier the interpretation of the zero peak as an NLR component is not consistent with the observed width and blue displacement of the zero peak. The zero peak was even broader than the red peak during the times when this feature rivaled it in intensity. We note a possible blueshift (~ 200 km s^{-1}—close to the value for the zero peak) of the central dip in the difference spectrum of Alloin et al. (1988). If the zero peak is an independent variable BLR component, it would make interpretation of the difference spectrum very dangerous.

3.3. *Multifrequency Continuum*

The continuum fluxes for IC 4329A and Akn 120 in the range from 20 cm to 10 keV are plotted in Figures 2*a* and 2*b*, respectively. Data sources are listed in the caption of Figure 2. Present data cannot offer a simultaneous view across the continuum, but flux values at different epochs are reported, in order to (at least) illustrate the range in the variations of the ionizing and optical continuum. We can quantify the level of variation in IC 4329A from *EXOSAT* spectra where a factor of $\approx 1.6 \sim 2$ is observed in the hard X-ray range (2 keV $< E <$ 10 keV). The same observations showed that the flux in the soft X-ray range (0.05 $< E <$ 2 keV) did not vary (Grandi et al. 1991). Akn 120 is also known to be variable by a factor of ≈ 2 at UV wavelengths (Turner & Pounds 1989). Perhaps the most striking continuum feature in IC 4329A is the impressive decrease at optical and UV wavelengths. No UV continuum is detected above the noise level in the short-wavelength range of *IUE*, while in the long-wavelength range, only faint emission steeply decreasing from 3100 to 2800 Å is present. The UV spectrum of Akn 120 is rather typical of Seyfert 1 galaxies, while contrarily, no emission lines are detected in the *IUE* spectra of IC 4329A. If we assume an intrinsic ratio of Lyα and C IV λ1459 to Hα comparable to the values for Akn 120, the

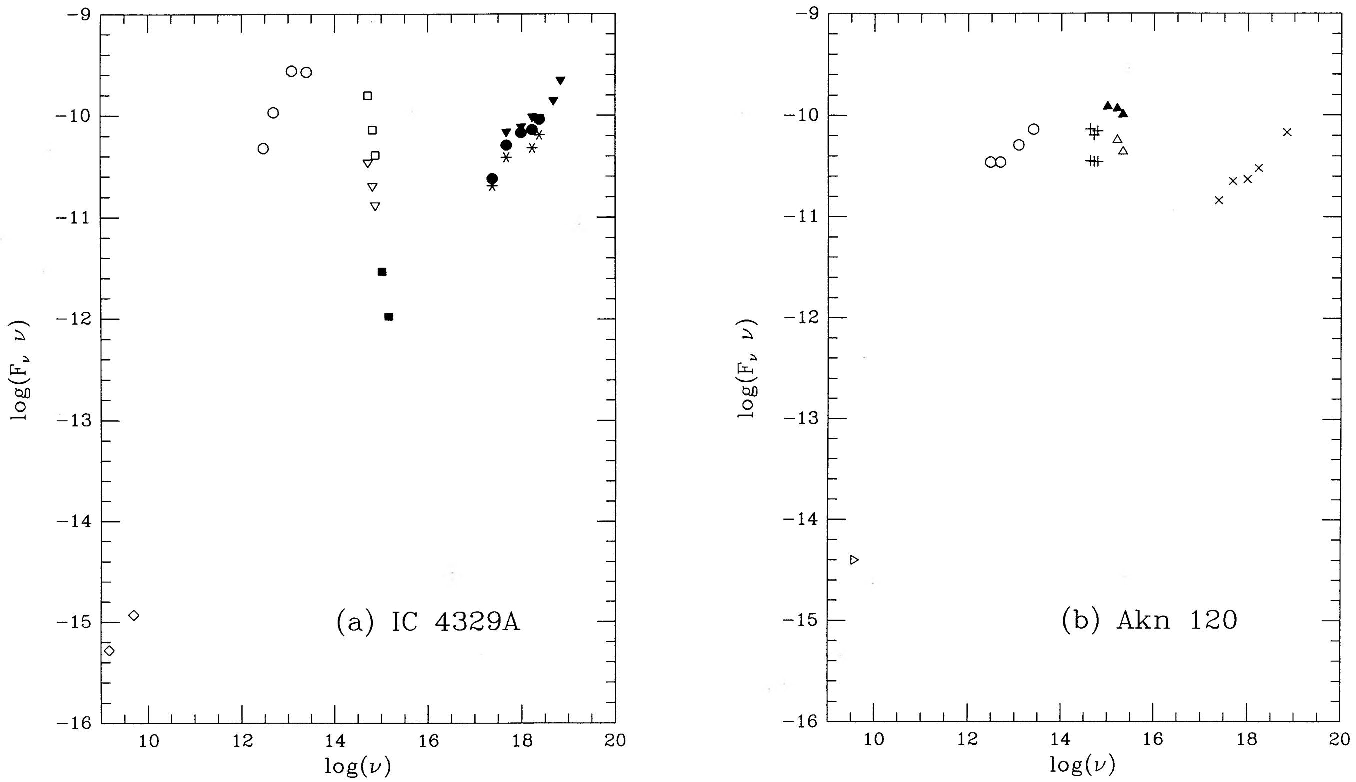

FIG. 2.—Multifrequency continuum of (*a*) IC 4329A and (*b*) Akn 120. *Diamond*: Dahari & de Robertis (1988); *sideways triangle*: Mazzarella & Balzano (1986); *open circle*: *IRAS* data as reported by Dahari & de Robertis (1988); *open square*: Morris & Ward (1988): 1984 June 5; *open downward triangle*: Fricke & Kollatschny (1989): 1985 February 18; *plus sign*: Alloin et al. (1988); *filled square*: archive *IUE* observations (unpublished); *filled upward triangle*: archive *IUE* observations: 1982 March 14; *open upward triangle*: archive *IUE* observations: 1980 October 22; *asterisk:* Turner & Pounds (1989): 1984 June 19; *filled circle*: archive *EXOSAT* spectra (Grandi et al. 1992): 1985 July 31; *downward triangle*: Yamauchi, Piro, & Matsuoka (1990): 1989 July 9; *multicross sign*: Turner & Pounds (1989).

reddening $E(B-V) \approx 0.8$ will reduce the line fluxes below the noise level of the *IUE* spectra. The strong absorption at UV wavelengths makes it difficult to constrain the *big blue bump* in IC 4329A, whose shape in active galaxies is usually inferred from the continuum shape in the (rest) wavelength range 1200–2500 Å.

The large extinction in IC 4329A [$E(B-V) \approx 0.8$] is most probably due to the near edge-on orientation of the host galaxy. Thus, both continuum and emission lines are likely affected by the same amount of reddening. We note in passing that, since the galaxy is seen nearly edge-on, the value of $E(B-V) \approx 0.8$ provides an estimate of the reddening due to the passage of light from the nucleus through one-half galactic disk, for a galaxy of morphological type near Sa.

4. DISCUSSION

The striking similarities between the Balmer line profiles and profile variations in Akn 120 and IC 4329A suggest a similar response by the BLRs to continuum changes. This may be an indication that the profiles reflect very similar BLR kinematics/geometry. The similarity of IC 4329A and Akn 120 implies that some kind of *ordered* and *reproducible* phenomenon is taking place in the BLR. It argues against the idea that random motion in an ensemble of clouds is the main source of Doppler line broadening in the BLR. The reproducibility of peculiar emission-line profiles poses difficulties for the idea that several independently accreting objects can account for the properties of the Seyfert 1 spectra, as suggested by Weedman (1983). Although a link between starburst phenomena and nonthermal nuclear activity seems real (e.g., Wilson et al. 1986; Rafanelli & Marziani 1992), it is also difficult for models explaining the optical spectrum of Seyfert 1 galaxies as due to supernova explosions (e.g., Terlevich & Melnick 1988) to account for the nearly identical profile variations over a time scale of a few years, as seen in the spectra of the two galaxies.

The parameters leading to similar BLR structures do not seem to depend strongly upon the morphology of the host galaxy, since IC 4329A is a spiral galaxy of type near Sa, while Akn 120 has an (amorphous) elliptical-like appearance. Similarly, the strength of Fe II emission appears to vary considerably between objects with almost identical broad-line profiles. If Akn 120 is indeed an elliptical galaxy, it is particularly interesting that it shows much stronger Fe II than IC 4329A.

The profile similarity may reflect a similarity in some parameter related to the central engine, such as the mass, bolometric luminosity, Eddington ratio $\eta = L_{\rm bol}/L_{\rm Edd}$, or even the line-of-sight orientation. The Eddington ratio is a very important parameter, since it governs the structure of the expected accretion disk: if $\eta < 1$, a geometrically thin disk is expected to be present, while if $\eta \sim 1$, a thick structure is expected to form (see, e.g., Calvani, Marziani, & Padovani 1989). Perhaps the Balmer lines are being emitted by gas moving in a very ordered velocity field, as would be the case for a rotating disk. Another possibility is that the double peaks are the signature of a *binary BLR*.

4.1. *Estimate of Mass*, $L_{bol,\,\eta}$

The mass of the central accreting object can be estimated (with reasonable accuracy) under the assumption that rotational or infall motions are dominating in the BLR. The mass in these two cases is $M = v^2 r/G$ and $M = v^2 r/2G$, respectively. The FWZI provides an estimate of the radial velocity for the gas near $R_{\rm in}$, the innermost radius of the BLR. The value of $R_{\rm in}$ can be estimated from the number of ionizing photons emitted by the continuum source $\int_{\nu 0}^{\infty} L\nu \, d\nu/h\nu$, and the product of the ionization parameter Γ and electron density, n_e, since

$$R_{\rm in} = \left[\frac{\int_{\nu 0}^{\infty} (L_\nu \, d\nu/h\nu)}{4\pi c \Gamma n_e}\right]^{1/2} . \qquad (1)$$

We assume that $\Gamma \times n_e \approx 10^{9.6}$ cm^{-3}, following Padovani & Rafanelli (1988). The number of ionizing photons has been computed by extrapolating the power-law index computed between 1 and 10 keV (namely $\alpha \approx 0.74$ for IC 4329A and 0.8 for Akn 120) over the range from 0.2 up to 120 keV. The *Big Bump* has been taken into account by modeling the spectrum as a power law with spectral index $\alpha = 1.3$ between the Lyman limit and 0.2 keV. We estimate (assuming infall) $M \approx 1.21 \times 10^8 \, M_\odot$ for IC 4329A and $M \approx 2.26 \times 10^8 \, M_\odot$ for Akn 120. The bolometric luminosity has been computed for IC 4329A and Akn 120 after correcting the optical and UV continuum for reddening. We find $L_{\rm bol} \approx 1.95 \times 10^{44}$ ergs s^{-1} for IC 4329A, and $L_{\rm bol} \approx 2.60 \times 10^{44}$ ergs s^{-1} for Akn 120. Since the Eddington luminosity is $L_{\rm Edd} = 1.3 \times 10^{38} \, (M/M_\odot)$ ergs s^{-1}, both objects appear to radiate at a very sub-Eddington rate, $\eta \approx 0.015$–0.020. Changes in the ionizing flux by a factor ≈ 2 affect the bolometric luminosity by a factor ≈ 1.6. Hence the Eddington ratio remains < 1. Since these values of η are typical for Seyfert 1 galaxies, and no changes in the structure of the accretion disk are expected, it appears that these parameters (mass, $L_{\rm bol}$, η) alone cannot account for the peculiarities observed in the spectra. Although IC 4329A and Akn 120 are luminous Seyfert galaxies, their bolometric luminosities are not extraordinarily large. They are both near the nominal absolute magnitude ($M_V = -23.0$, $H_0 = 50$ km s^{-1} Mpc^{-1}) boundary between quasars and Seyfert galaxies. We will discuss later the possibility that the central engine is being viewed at a special orientation.

4.2. *Accretion Disk*

Emission by an accretion disk is naively suggested by the *double-peak* structure in the Balmer lines. We must distinguish here between a double-peak structure in the raw spectrum and one in the difference spectrum. It would however be difficult for a simple model of a rotating disk to explain the *entire* Hβ and Hα emission in either case. In general, gravitational plus transverse Doppler redshifts plus Doppler boosting should be considered in order to explain the observed profiles. The most straightforward models predict a strong blue peak and redshifted base for line emission originating from the disk (Chen et al. 1989; Chen & Halpern 1989). At larger values of $R_{\rm out}$ these effects tend to diminish, and the profile in general would show a red asymmetry with a possible small blueward shift of the peak (AR, or AR, B in Sulentic 1989). Since it is difficult to reconcile a strong displaced red peak with the simple radiative accretion disk model, no clear accretion disk signature can be readily isolated in these unusual objects. The structure in the raw spectrum is also not a good fit to disk models because the cenral dip shows a displacement of about 10^3 km s^{-1} with respect to the systemic velocity. One possible scenario might involve a disk radiating at large R producing the central peak with a separate infalling component producing the red peak. In this view the red peak is an independent component, perhaps in a double stream configuration (Zheng, Binette, & Sulentic 1991), and its variations might be uncorrelated with those of the zero peak.

Alloin et al. (1988) suggested that the BLR of Akn 120 is made of two regions, one of which corresponds to the accretion disk. Their suggestion is based upon the difference spectrum of the line profiles in the *high*- and *low*-luminosity phase which may show a double-peaked structure. We have discussed earlier the possible problems with the difference spectrum. If a contribution from a disk is present, we must hypothesize that it is switched on as a consequence of particular events. This can have strong consequences upon the possibility of effectively revealing the disk and will be discussed in a further study (Marziani et al. 1991). However, the two peaks revealed in the difference spectrum should vary in phase. The Hβ profile of Akn 120, taken on 1987 December 27, clearly shows that this is not the case, since the blue shoulder is at the same intensity level as the red peak (P. Rafanelli, private communication). Older data support this contention. A spectrum of Akn 120 is presented by Foltz et al. (1981) shows a possible blue peak that is stronger than the more commonly observed red feature.

Assuming that the difference spectrum for Akn 120 is indeed due to a disk, another difficulty for the interpretation of profile variations in the disk model of Alloin et al. (1988) arises from considerations of the energy balance in the BLR. In the following, we will restrict our calculation to AkN 120, because of the less uncertain reddening estimate. Geometrical parameters for the best-fit disk of the difference spectrum are $R_{\rm out} = 2.2 \times 10^4 \, R_g$ and $R_{\rm in} \approx 400 R_g$ assuming $\sin i = \sqrt{2}/2$. Dumont & Collin-Souffrin (1990a, b) have suggested that the outer region of the accretion disk has physical conditions suitable for the emission of a low-ionization spectrum. Dumont & Collin-Souffrin pointed out that the disk should be illuminated by an external source in order to produce emission of a line spectrum. They suggested two illumination models:

1. Two point sources located at height A above the disk plane (point sources model, PSM). This provides an incident flux per unit area:

$$F_{\rm inc} = f_{\rm inc} \frac{L_{\rm ion}}{4\pi} \frac{A}{(R^2 + A^2)^{3/2}} , \qquad (2)$$

where $f_{\rm inc}$ is the percentage of continuum radiated toward the disk (we assume $f_{\rm inc} = 0.5$, as is the case for two isotropically emitting sources);

2. A diffuse central source of radius $R_{\rm min}$ (diffusion model, DM), giving an incident flux per unit area

$$F_{\rm inc} = f_r \frac{L_{\rm ion}}{4\pi R^2} \left(\frac{R_{\rm min}}{R}\right)^g , \qquad (3)$$

where the fraction of flux scattered toward the disk is now f_r/g, if $g > 0$ (see Dumont & Collin-Souffrin 1990a for details).

Variations in the Hβ luminosity assumed due to the disk are ≈ 2–3 times the total line luminosity in the low state. If the ionizing continuum changes *switch on* the illumination of the disk, we can compute the ionizing luminosity intercepted by the disk, by integrating over the disk area:

$$\text{PSM:} \int_{R_{\rm in}}^{R_{\rm out}} F_{\rm inc} \, d\Sigma = \frac{L_{\rm ion}}{4} A \left(\frac{1}{\sqrt{R_{\rm in}^2 + A^2}} - \frac{1}{\sqrt{R_{\rm out}^2 + A^2}}\right) , \qquad (4)$$

and

$$\mathrm{DM}: \int_{R_{\rm in}}^{R_{\rm out}} F_{\rm inc}\, d\Sigma = f_r \frac{L_{\rm ion}}{2} \frac{R^g_{\rm min}}{g} \left(\frac{1}{R^g_{\rm in}} - \frac{1}{R^g_{\rm out}} \right) . \qquad (5)$$

Note that the right sides of equations (4) and (5) give the covering factor f_a of the disk times $L_{\rm ion}$.

We adopt the geometrical parameters of the disk deduced earlier. The number of ionizing photons needed to sustain the Hβ change can be easily computed assuming case B of nebular recombination theory. The Hβ luminosity was previously divided by a factor ε which expresses the enhancement of the line due to collisional excitation. The estimate from a comparison of the observed Lyα/Hβ ratio and expected from case B is $\varepsilon \approx 5$. However, according to Dumont & Collin-Souffrin, the ratio Lyα/Hβ depends upon the illumination model and can be larger than the previous value. For the PSM, ε could be ≈ 100 if $A \sim 10^3 R_g$, decreasing to $\varepsilon \approx 30$ for $A \sim 10^4 R_g$ and $\varepsilon \approx 22$ for $A \sim 10^5 R_g$. Since changes in the continuum are a factor of ≈ 2, the expected number of ionizing photons is not able to produce the changes in the Hβ luminosity, unless the covering factor of the disk tends to the limiting value 0.5. This result is independent of the exact value of ε and would imply that A is very large $\gtrsim 1000 R_g$. This condition is unlikely to be satisfied, since the ionizing continuum is believed to be produced in a region which is contained within a radius $R \lesssim 100 R_g$. Furthermore, this estimate has been made assuming the most favorable conditions in order to increase the covering factor and hence to diminish A.

The alternate possibility involves a disk that is illuminated by a diffuse source. The case $g = 0.8$ corresponds to diffusion by a nuclear wind (Mardaljevic et al. 1988). The high value of $\varepsilon \approx 55$ would require a diffusion sphere of radius $R \simeq 200 R_g$. However $g = 0.5$ might be a more realistic value since it doesn't require injection of matter in the diffusion sphere (Dumont & Collin-Souffrin 1990a). In this case, $R_{\rm min} \simeq 650 R_g$ would imply that the scattering medium extends beyond the inner radius of the disk. The case $g = 0.0$ corresponds to a model where matter is continuously injected by supernova explosions or by mass loss from post–main-sequence stars (Dumont & Collin-Souffrin 1990b; Norman & Scoville 1988). It has the advantage that the total flux is independent of $R_{\rm min}$, since the scattering medium is spread over the disk. The total flux intercepted by the disk is $0.8 L_{\rm ion} \ln (R_{\rm out}/R_{\rm in})$, which in the case of Akn 120 will be $0.8 L_{\rm ion}$. In this extreme case it is possible to account for the flux variation in the Balmer lines.

It appears to be difficult for a disk model (as far as the illumination models of Dumont & Collin-Souffrin are concerned) to explain the variations in the Balmer line profiles of Akn 120 and hence IC 4329A, unless:

1. The continuum variations are poorly constrained and are much larger than a factor ≈ 2;
2. The continuum is not emitted/scattered isotropically;
3. The correction for reddening applied to the lines is too high.

Although the first condition should be tested by X-ray monitoring of these objects, the latter two seem to be rather unlikely.

4.3. *Binary Black Hole*

The Balmer line profiles observed in Akn 120 and IC 4329A could be due to a binary BLR, that is, with two BLR surrounding a pair of back holes orbiting around their center of mass. This idea was suggested by Gaskell (e.g., Gaskell 1988 for a review), and it has been observationally tested for OX 169 by Stockton & Farnham (1991). In this scenario, the radial velocity shifts of the zero and red peaks could be attributed to the projection along the line of sight of the orbital motion of each black hole. The ratio of the velocity shift of the zero and red peak (with respect to the reference frame provided by the NLR) allows one to estimate the mass ratio of the two black holes, which should be $\approx 1/6$ for Akn 120 and $\approx 1/36$ for IC 4329A. Monitoring of the line profiles should reveal changes in the radial velocity of the peaks. To the best of our knowledge, any variation in the zero and red peak radial velocities is less than the estimated errors in the peak radial velocity, ± 100 km s^{-1}. This covers the time period since the discovery of spectral variability in Akn 120 and since the data were published by Wilson & Penston (1979) for IC 4329A. A lower limit to the sum of the masses can be set through the relation $M_{\rm S} \gtrsim (1/338) P V^3_{r,1000}$, where P is the period in yr, and $V_{r,1000}$ is the radial velocity of the red peak in 1000 km s^{-1} (cf. Halpern & Filippenko 1988). The maximum orbital phase change should be $\Delta\phi \lesssim 27°$ in ~ 10 yr, which would correspond to a period $P \gtrsim 132$ yr. We find $M \gtrsim 2.3 \times 10^8\, M_\odot$, which is reasonable for Seyfert 1 galaxies. Nevertheless, given the different black hole mass ratio, it is difficult to explain the similarity in line profiles and in line-profile changes in Akn 120 and IC 4329A.

4.4. *Further Clues*

Self-absorption in the Balmer lines appears unlikely, since the dip in the undifferenced spectra of both objects is displaced by ≈ 1000 km s^{-1} with respect to line center (assuming that the rest frame of the galaxy is also that of the BLR). It is useful to recall that the central dip in the *profile difference* could be due to self-absorption in very high density gas, rather than a reflection of the rotational kinematics of the emitting gas. If the density is as high as $n_e \approx 10^{12}$–10^{13} cm^{-3}, as in stellar chromospheres, self-absorption in the Balmer lines should arise. Such high-density gas, located at the inner edge of the BLR (estimated as ≈ 2 lt-months for Akn 120), could have $\Gamma \approx 1 \times 10^{-4}$, and would thus be able to emit the observed low-ionization spectrum. This view is supported by the decrease of the Balmer decrement between the low- and high-luminosity states.

Morris & Ward (1988) found that the O I λ8446 profiles are very similar in the two objects. The profile of the O I λ8446 line is in turn similar to the core of the Hβ profile. Since the O I λ8446 line is a fluorescence line produced only by gas very optically thick to the Lyman continuum, this supports the assumption that the line cores are emitted by optically thick gas, as expected from photoionization models. Morris & Ward (1988) found moreover that Akn 120 and IC 4329A are the only two AGNs in their sample for which emission from optically thin gas is likely to be present. For both objects, the optically thin emission is present in the blue wing of the Balmer lines.

The reddening-corrected luminosity for Hβ in IC 4329A and Akn 120 is rather high relative to other Seyfert galaxies. A comparison with the values provided by Padovani & Rafanelli (1988) shows that Akn 120 and IC 4329A have the highest Hβ luminosities in their sample of Seyfert 1 galaxies. Since the BLR geometry is likely to be flattened (e.g., Osterbrock 1979), existence of a preferential plane/axis is a rather likely possibility. This plane could be identified with the plane of the accretion disk, which cannot generally be identified with the principal plane of the galaxy (Tohline & Osterbrock 1982).

Several forms of evidence suggest that at least some Seyfert 2 galaxies have a BLR hidden by a torus of cold obscuring matter (e.g., Wilson, Ward, & Haniff 1988; Miller 1988). If the differences between Seyfert 2, intermediate Seyfert, and Seyfert 1 are galaxies due only to a projection effect, continuity arguments would suggest that the central engines of Akn 120 and IC 4329A are oriented rather "face on" toward the observer. The rarity of Balmer line profiles like those seen in the Akn 120 and IC 4329A also points toward an unusual orientation or extremum in the viewing angle.

The detection of optically thin gas also favors the absence of obscuration "intrinsic" to the central engine, as might be caused by a molecular torus, since the optically thin gas emitting the wings of the Balmer lines should be located in the innermost part of the BLR (e.g., Ferland, Korista, & Peterson 1990). The strong contribution of such gas revealed only in the blue wings of the lines suggests that it could be associated with an outflowing component. Zheng et al. (1990) have indeed produced a good fit to the profile of Akn 120 using a model that assumes biconical outflow for the gas clouds.

Moreover, we think that the study (currently underway) of small groups of objects with peculiar and variable profiles (as is the case for Akn 120, IC 4329A and, maybe, OX 169; 3C 390.3 and 3C 382; Arp 102B and 3C 332 and some others) may help to settle some fundamental questions concerning the BLR and the nature of the central engine. Such studies should be able to clarify whether a unique geometrical model can explain the BLR, or whether one should expect the presence of different geometries in different object classes.

We considered the hypothesis that variations in emission-line fluxes from the low- to the high-luminosity phase might be due to the switching on of disk emission. This hypothesis has its foundation in the possible double-peaked component found in the difference spectra of the Balmer lines in Akn 120 and IC 4239A. From our discussion it follows that the size of the region scattering/emitting the continuum must be rather extreme in order to satisfy the illumination models proposed by Dumont & Collin-Souffrin (1990a). We propose that some spectral peculiarities in Akn 120 and IC 4329A could be more easily explained if the orientation of the *central engine* is near face-on.

5. CONCLUSIONS AND FURTHER WORK

The profile variations observed in IC 4329A and Akn 120 make these objects of great value for understanding the BLR structure. In particular, observations of the Paschen continuum and lines should be performed in order to test whether optical depth effects in the Balmer lines are playing a role. IC 4329A deserves much more attention than it has had in the past. It is a good candidate for an extensive spectroscopic monitoring campaign.

We are grateful to P. Rafanelli for having provided us with a spectrum of Akn 120 taken in 1987, P. Grandi for useful information about the X-ray spectrum of IC 4329A, and W. Zheng for helpful comments. P. M. would like to acknowledge the hospitality of the University of Alabama at Tuscaloosa, where part of this work was done. J. W. S. and P. M. are grateful for support from NSF/State of Alabama EPSCoR grant RII-8996152.

REFERENCES

Alloin, D., Boisson, C., & Pelat, D. 1988, A&A, 200, 17
Calvani, M., Marziani, P., & Padovani, P. 1989, in Proc. Italian Conf. on General Relativity and Gravitational Physics, ed. M. Cerdonio et al. (Singapore: World Scientific), 102
Chen, K., & Halpern, J. P. 1989, ApJ, 344, 115
Chen, K., Halpern, J. P., & Filippenko, A. V. 1989, ApJ, 339, 742
Dahari, O., & de Robertis, M. M. 1988, ApJS, 67, 249
de Bruyn, A. G. 1980, Highlights Astron., 5, 631
Disney, M. J. 1973, ApJ, 181, 55
Dumont, A. M., & Collin-Souffrin, S. 1990a, A&A, 229, 302
———. 1990b, A&A, 229, 313
———. 1990c, A&A, 83, 71
Ferland, G. J., Korista, K. T., & Peterson, B. M. 1990, ApJ, 363, L21
Foltz, C. B., Peterson, B. M., Capriotti, E. R., Byard, P. L., Bertram, R., & Lawrie, D. G. 1981, ApJ, 250, 508
Foltz, C. B., Wilkes, B. J., & Peterson, B. M. 1983, AJ, 88, 1072
Fricke, K. J., & Kollatschny, R. F. 1989, A&AS, 77, 75
Gaskel, C. M. 1988, in Active Galactic Nuclei, ed. H. R. Miller & P. J. Witta (Berlin: Springer), 61
Grandi, P., Tagliaferri, G., Giommi, P., Barr, P., & Palumbo, G. C. G. 1992, ApJS, in press
Halpern, J. P. 1990, ApJ, 365, 51
Halpern, J. P., & Filippenko, A. V. 1988, Nature, 331, 46
Malkan, M. M., & Sargent, W. L. W. 1982, ApJ, 254, 22
Mardaljevic, J., Raine, D. J., & Walsh, D. 1988, Ap. Lett. Comm., 26, 357
Marziani, P. 1991, Ph.D. thesis, SISSA, Trieste
Marziani, P., et al. 1992, in preparation
Mazzarella, J., & Balzano, V. A. 1986, ApJS, 62, 751
Miller, J. S. 1988, in Active Galactic Nuclei, ed. H. R. Miller & P. J. Wiita (Berlin: Springer), 112
Morris, S. L., & Ward, M. J. 1988, MNRAS, 230, 639
Norman, C., & Scoville, N. 1988, ApJ, 332, 134
Osterbrock, D. E. 1979, AJ, 84, 901
Osterbrock, D. E., & Phillips, M. M. 1977, PASP, 89, 251
Padovani, P., & Rafanelli, P. 1988, A&A, 205, 53
Peterson, B. M., Foltz, C. B., Miller, H. R., Wagner, R. M., Crenshaw, D. M., Meyers, K. A., & Byard, P. L. 1983, AJ, 88, 926
Rafanelli, P., & Marziani, P. 1992, AJ, 103, 743
Schulz, H., & Rafanelli, P. 1981, A&A, 103, 216
Singh, K. P., Rao, A. R., & Vahia, M. N. 1991, ApJ, 377, 417
Stirpe, G., de Bruyn, A. G., & van Groningen, E. 1988, A&A, 200, 9
Stockton, A., & Farnham, J. 1991, ApJ, 371, 525
Stone, R. P. S. 1977, ApJ, 218, 767
Sulentic, J. W. 1989, ApJ, 343, 54
Sulentic, J. W., Calvani, M., Marziani, P., & Zheng, W. 1990, ApJ, 355, 15
Terlevich, R., & Melnick, J. 1988, Nature, 333, 239
Tohline, J., & Osterbrock, D. E. 1982, ApJ, 252, 49
Turner, T. J., & Pounds, K. A. 1989, MNRAS, 240, 833
Ulrich, M.-H. 1991, in IAU Colloq. 129, Structure and Emission Properties of Accretion Disks, ed. C. Bertout, S. Collin-Souffrin, J. P. Lasota, & J. Tran Than Van (Dordrecht: Reidel), 43
Weedman, D. W. 1983, ApJ, 266, 479
Wilson, A. S., Baldwin, J. A., Sun, S. D., & Wright, A. E. 1986, ApJ, 310, 121
Wilson, A. S., & Penston, M. V. 1979, ApJ, 232, 389
Wilson, A. S., Ward, M., & Haniff, C. A. 1988, ApJ, 334, 121
Yamauchi, M., Piro, L., & Matsuoka, M. 1990, in 21st Internat. Cosmic Ray Conference (Adelaide), 1, 19
Zheng, W., Binette, L., & Sulentic, J. W. 1990, ApJ, 365, 115