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MONITORING Lyα EMISSION FROM THE BLAZAR 3C 279

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ABSTRACT

The blazar 3C 279 is well studied and shows frequent large continuum flares from radio to γ-ray wavelengths. There have been a number of multiwavelength observations of 3C 279, and hence there are extensive ultraviolet data for this object available in the UV archives. In this paper we present Lyα emission line measurements for 3C 279 using all the archival *IUE* SWP spectra from 1988 to 1996 and all archival *Hubble Space Telescope* (*HST*) Faint Object Spectrograph (FOS) G190H spectra from 1992 to 1996.

Individual archival *IUE* spectra of 3C 279 show weak Lyα emission at $\sim$1868 Å ($z = 0.536$), which is easily seen in the co-added data. The Lyα emission is observed in all the *HST*/FOS spectra. The strength of Lyα is nearly constant ($\sim 5 \times 10^{-14}$ ergs cm^{-2} s^{-1}), while the 1750 Å continuum varies by a factor of $\sim$50, from $\sim$0.6 to 31.6×10^{-15} ergs cm^{-2} s^{-1} Å^{-1}.

The behavior of the Lyα emission line flux and continuum flux is similar to that of the only other well observed blazar, 3C 273, which shows constant line flux while the continuum varies by a factor of $\sim$3. This near-constancy of emission-line flux in the two best-studied blazars suggests that the highly variable beamed continuum is not a significant source of photoionization for the gas. Some other source, such as thermal emission from an accretion disk, must be providing a significant fraction of the photoionizing flux in these objects. The large amplitude variability seen at γ-ray energies must be due to changes in the energetic electrons in the jet rather than changes in the external photon field.

Subject headings: galaxies: active — quasars: individual (3C 279) — ultraviolet: galaxies

1. INTRODUCTION

Blazars as a class of active galactic nuclei (AGNs) exhibit a smooth, highly variable, highly polarized IR-UV continuum. According to "Unified Schemes" for radio-loud AGNs (Browne & Murphy 1987; Barthel 1989; Antonucci 1993), the observed continuum comprises a mixture of thermal radiation and nonthermal beamed radiation. The thermal, unbeamed component extending from the UV to the soft X-rays may originate from a hot accretion disk, as in radio-quiet AGNs. The nonthermal component extending from radio to γ-ray wavelengths is thought to be relativistically beamed synchrotron radiation, possibly originating from a twin jet (Königl 1981). This beamed component is highly variable and highly polarized. Blazars are thought to be those objects viewed at a small angle to the beaming axis and thus dominated by the nonthermal component (Urry & Padovani 1995). Some blazars exhibit a broad emission line spectrum similar to Seyfert galaxies and radio-quiet quasars, particularly when the continuum is faint (the exceptions are classified as BL Lac objects; see, however, Scarpa & Falomo 1997). Although blazars are highly variable and show broad emission lines, their line variability studies have received relatively little attention to date.

In recent years the study of broad emission line variability has been recognized as a powerful diagnostic of the broad-line region in Seyfert 1 galaxies (Peterson 1993). In the best-monitored AGNs, high-ionization lines like Lyα and C IV are more rapidly variable (factors of $\sim$10) than low-ionization lines like Mg II or Hα (e.g., Clavel et al. 1991; Peterson 1993). Hence, the high-ionization lines are extremely powerful probes of the smallest, most variable regions. Yet Lyα emission line variability has been investigated in only a few high-luminosity radio-loud objects (Bregman et al. 1986; Pérez et al. 1989; Gondhalekar 1990; Ulrich, Courvoisier, & Wamsteker 1993; Webb et al. 1994; Scarpa, Falomo, & Pian 1995; Wamsteker et al. 1997). Most of these studies indicate that emission-line variability timescales are on the order of months and the variability is confined to the line cores. However, these objects either are not typical blazars (i.e., their continuum is not dominated by a beamed component) or have only a handful of observations.

It is not clear whether the broad emission lines in blazars behave differently from the broad emission lines observed in Seyfert 1 galaxies. Further, what is the role of the blazar jet in photoionizing the emission lines; that is, what is the effect of the beamed blazar light on the line-emitting region? What is the structure of the broad-line region gas? Some investigations are starting to address these questions (e.g., Corbett et al. 1996).

3C 279 is an excellent target to study emission-line variability in blazars, since it is a highly variable, bright radio source. It is also one of the brightest known extragalactic γ-ray sources (Hartman et al. 1992; von Montigny et al. 1995), is highly variable at X-ray and γ-ray energies (Makino et al. 1989; Kniffen et al. 1993; Maraschi et al. 1994), and is one of the clearest cases of relativistic beaming (Dondi & Ghisellini 1995). It shows highly variable optical polarization (9%–45%; Angel & Stockman 1980; Impey & Tapia 1990; Mead et al. 1990) and has been one of the most intensively monitored objects of the blazar class. Finally, it is one of two emission-line blazars with extensive archival UV spectra. In this paper we report the Lyα emission line history for 3C 279, which has not been as thoroughly investigated as the continuum, and its relation to the continuum

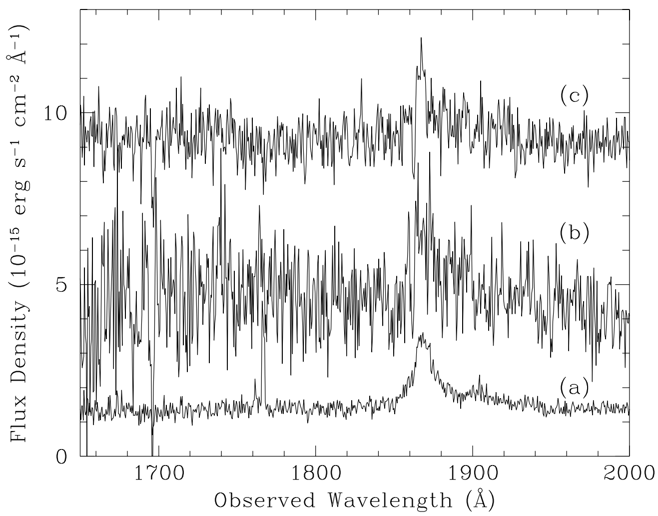

FIG. 1.—The three *HST*/FOS spectra of 3C 279. Note that even in the low state, the Lyα line is clearly visible at 1868 Å. (*a*) 1992, (*b*) 1994, and (*c*) 1996.

variability. The analysis is based on archival ultraviolet data from both the *IUE* and the *Hubble Space Telescope* (*HST*).

2. OBSERVATIONS

2.1. *HST*/*FOS Data*

Between 1992 and 1996, 3C 279 was observed three times with the *HST* Faint Object Spectrograph (FOS). The 1992 observation covers the wavelength range 1150–4750 Å and has been discussed in great detail by Netzer et al. (1994), who note that the spectrum shows the Lyα, C IV λ1549, C III] λ1909, Mg II λ2800, and Hβ lines. The Lyα, C III], and Hβ line profiles are fairly symmetric, while C IV and Mg II have substantial red wings. During this period 3C 279 was in a faint state, with a clearly visible Lyα emission line (see Fig. 1). The 1994 and 1996 observations cover the wavelength range 1150–2312 Å. Both these observations were obtained when 3C 279 showed a flare. Once again, in these FOS spectra the Lyα is still easily visible (see Fig. 1), but the signal-to-noise ratio (S/N) is not as good as in the 1992 observation.

We retrieved the FOS data from the *HST* archive and recalibrated them using the best reference files, as recommended by the *HST* Data Handbook (Version 2). The details of each observation are given in Table 1 and the spectra are shown in Figure 1. The recalibration of the FOS spectra was necessary because the older spectra are calibrated using different procedures and could not otherwise be directly compared with more recent spectra. The recalibrated FOS spectra can also be directly compared with the *IUE* spectra, since both the *HST* and *IUE* spectrophotometric calibrations use the model white dwarf reference scale (Colina & Bohlin 1994). In fact, based on an analysis of Seyfert galaxies observed simultaneously with FOS and *IUE*, absolute flux differences are $\lesssim 5\%$ (Koratkar et al. 1997).

The 1994 FOS observation was obtained using two gratings (G130H and G190H). During the latter observation, as a result of reacquisition problems, the target was partially out of the aperture and the G190H spectrum was affected. We have therefore added a constant flux to the G190H observation to align the data with the G130H spectrum. The errors given in Table 1 for this spectrum (y2ey0606) reflect our uncertainty (10%) in applying this procedure.

2.2. *IUE Data*

Between 1988 and 1996, 3C 279 was observed with *IUE* many times with both the short-wavelength and long-wavelength cameras. The long-wavelength (LWP/LWR) spectra are affected by low detector sensitivity and, increasingly with time, by scattered light, hence emission lines longward of the Lyα line are difficult to detect. In this paper, we concentrate on the Lyα line, and thus only the 15 short-wavelength (SWP) camera observations are discussed further.

TABLE 1

FITS TO THE INDIVIDUAL SPECTRA

Image/Spectrum	Date	Exposure Time (s)	$F_{\lambda 1750}$ ($\times 10^{-15}$ ergs cm^{-2} s^{-1} Å^{-1})	$F_{\mathrm{Ly}\alpha}$ ($\times 10^{-14}$ ergs cm^{-2} s^{-1})
SWP 33864......	1988 Jul 5	6000	29.43 ± 0.36	12.17 ± 4.96
SWP 33865......	1988 Jul 5	10200	31.55 ± 0.29	6.63 ± 1.95
SWP 35443......	1989 Jan 28	10740	13.83 ± 0.21	11.20[a]
SWP 36420......	1989 Jun 8	13200	17.09 ± 0.17	16.35[a]
SWP 40489......	1990 Dec 29	14400	18.34 ± 0.14	...[b]
SWP 42132......	1991 Jul 27	14400	11.69 ± 0.11	8.09 ± 1.60
SWP 44806......	1992 May 29	10800	12.24 ± 0.26	11.19 ± 3.50
SWP 46649......	1993 Jan 2	13200	1.42 ± 0.12	4.52 ± 1.29
SWP 46653......	1993 Jan 3	36000	1.47 ± 0.11	3.88 ± 0.98
SWP 46657......	1993 Jan 4	39600	1.27 ± 0.10	5.33 ± 0.70
SWP 46662......	1993 Jan 5	39600	1.03 ± 0.10	3.72[a]
SWP 49681......	1993 Dec 24	12000	3.45 ± 0.21	7.38 ± 1.33
SWP 49686......	1993 Dec 25	19800	4.19 ± 0.24	4.44 ± 1.15
SWP 53261......	1995 Jan 3	16800	0.60 ± 0.10	5.38[a]
SWP 56635......	1996 Jan 25	19500	4.59 ± 0.31	5.27 ± 1.55
y0pe0b02/3	1992 Apr 8	2250	1.89 ± 0.03	5.22 ± 0.56
y2ey0606.........	1994 Jun 5	1980	6.12 ± 0.08	5.86 ± 1.41
y32j0605	1996 Jan 8	2250	5.71 ± 0.03	4.04 ± 1.19

[a] The amplitude of Lyα is less than the rms fluctuations about the best-fit power-law model, so values given are 5 σ upper limits. A high background is seen in some of the spectra.

[b] A cosmic ray hit exactly on the Lyα line, and the flux not measured.

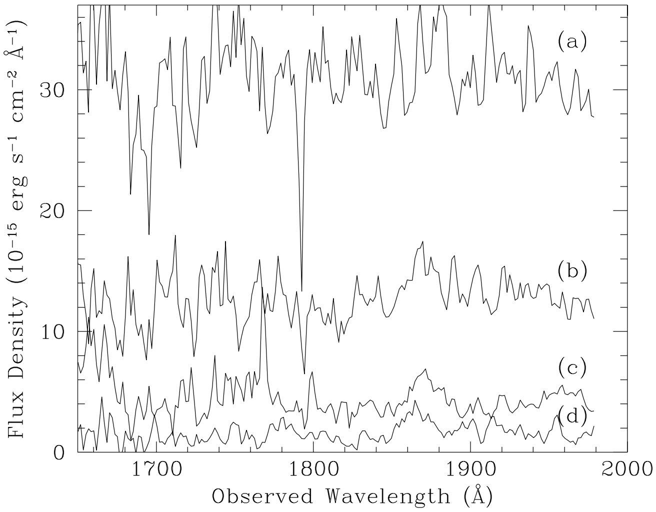

FIG. 2.—The co-added *IUE* spectra of 3C 279 in four intensity states, as defined in § 2.2 (see also Table 2). In all continuum flux ranges the Lyα line is visible at 1868 Å. (*a*) "High" spectrum, (*b*) "medium" spectrum, (*c*) "low" spectrum, (*d*) "very low" spectrum.

A careful inspection of the 15 line-by-line spectral images for flaws showed that in one case (SWP 40489), the Lyα spectral region was contaminated by a cosmic ray. This spectrum was therefore rejected from further analysis.

All the line-by-line spectral images were also analyzed to determine the background contribution. A comparison of the average flux numbers in the 1866–1872 Å interval centered on the object spectrum and on the background (10 lines away on either side of the object spectrum) showed that in SWP 46662 and SWP 53261 the background contribution exceeded 90% of the signal + background emission. Therefore, the Lyα emission line flux measurements for these spectra in Table 1 are 5 σ upper limits. These noisy spectra have not been used in the co-addition described below.

All the spectra were extracted from the line-by-line image files using the NEWSIPS technique being implemented in the final *IUE* archive. A summary of the NEWSIPS extraction technique can be found in Nichols & Linsky (1996). The details of each observation are given in Table 1. All the 1992–1993 spectra are underexposed, but some signal is present. *IUE* spectral regions with known artifacts, at 1278–1279 Å, 1450–1550 Å, and 1663 Å (Crenshaw, Norman, & Bruegman 1990), were excluded from the analysis.

The improved S/N obtained through NEWSIPS allowed sufficient contrast in the SWP spectra between the continuum and Lyα, even in the lowest states, to perform for the first time a systematic study of the emission line in this source. The Lyα emission feature that is clearly present in the FOS data is also seen in all but four individual SWP spectra (see Table 1). Recently, the sensitivity degradation correction for SWP spectra obtained after 1993 has been determined. This correction is time dependent and can be up to 5% in 1996 (Imhoff 1997). This correction has not yet been implemented in the final *IUE* archive, however, so we have conservatively added a 5% error in quadrature to the uncertainties of the continuum and line fluxes for spectra obtained after 1993.

To improve the S/N of the Lyα emission line, we binned the spectra in four groups depending on the continuum flux at 1750 Å. The SWP spectra in each group were then co-added, as follows: the "high spectrum" was generated by co-adding all spectra with $f_{\rm cont} > 2 \times 10^{-14}$ ergs cm^{-2} s^{-1} Å^{-1}, the "medium spectrum" is a co-addition of all spectra with $8 \times 10^{-15} < f_{\rm cont} \leq 2 \times 10^{-14}$ ergs cm^{-2} s^{-1} Å^{-1}, the "low spectrum" is a co-addition of all spectra with $3 \times 10^{-15} < f_{\rm cont} \leq 8 \times 10^{-15}$ ergs cm^{-2} s^{-1} Å^{-1}, and the "very low spectrum" includes all spectra with $1 \times 10^{-15} \leq f_{\rm cont} \leq 3 \times 10^{-15}$ ergs cm^{-2} s^{-1} Å^{-1}. In Figure 2 we show the four co-added spectra. The Lyα emission line is easily seen at $\sim$1868 Å. The redshift measured from the *IUE* observations is in good agreement with the redshift determined from the high S/N FOS data (Netzer et al. 1994) given the wavelength uncertainty and the low S/N of the *IUE* spectra.

2.3. *Flux Measurements*

The Galactic hydrogen column density in the direction of 3C 279 is 2.22×10^{20} cm^{-2} (Elvis, Lockman, & Wilkes 1989), which implies $A_V = 0.13$, for a total-to-selective extinction ratio of $R = 3.1$. All the FOS and *IUE* spectra were dereddened assuming the Cardelli, Clayton, & Mathis (1989) extinction curve.

A simple power-law model was fitted to the dereddened spectra in the wavelength region 1230–1950 Å using the IRAF/STSDAS tool nfit1d. Wavelength regions affected by the *IUE* artifacts were excluded from the fits to the *IUE* spectra, as was the region around Lyα. We defined 1750 Å as the fiducial wavelength for continuum flux measurements because this region of the SWP spectrum is relatively free of *IUE* artifacts and line emission.

After subtracting the best-fit power-law continuum, the Lyα line was measured as follows. The 1992 FOS observation, which has the best S/N and spectral resolution, was accurately modeled with a multicomponent Gaussian fit using a minimalist approach (least number of free parameters). IRAF/STSDAS tool ngaussfit was used for this procedure. This model of the Lyα line was then used to fit the remaining two FOS spectra. Since these spectra have lower S/N, the observed wavelength of the Lyα line was fixed at 1868 Å (within the wavelength calibration error of

TABLE 2

FITS TO THE CO-ADDED SPECTRA

Image	Co-added Spectra	$F_{\lambda 1750}$ ($\times 10^{-15}$ ergs cm^{-2} s^{-1} Å^{-1})	$F_{\rm Ly\alpha}$ ($\times 10^{-14}$ ergs cm^{-2} s^{-1})
"High"	SWP 33864, SWP 33865	30.66 ± 0.47	10.86 ± 6.45
"Medium"	SWP 35443, SWP 36420 SWP 42132, SWP 44806	13.71 ± 0.36	5.00 ± 2.45
"Low"	SWP 49681, SWP 49686 SWP 56635	4.12 ± 0.14	5.26 ± 2.12
"Very low"......	SWP 46649, SWP 46653 SWP 46657	1.40 ± 0.11	4.20 ± 2.11

the FOS) and the widths and amplitudes were allowed to vary. We note here that all the FOS spectra show an intrinsic absorption feature in the Lyα emission line. These absorption features are discussed in detail by Chaffee et al. (1998).

Because of the low S/N ratio of the *IUE* data, the observed wavelength of the Lyα line was fixed at 1868 Å (within the wavelength calibration error of the *IUE*), and the line was modeled with a single Gaussian whose width and height were allowed to vary freely. A single Gaussian fit was sufficient for the *IUE* because of the low spectral resolution. In all but two spectra, the Lyα emission line is easily detected; in the exceptions (SWP 35443, SWP 36420) the Lyα region is very noisy.

The continuum fluxes at 1750 Å and the Lyα line fluxes, along with their associated uncertainties, are reported in Table 1 for the individual spectra and in Table 2 for the co-added spectra.

3. RESULTS AND DISCUSSION

Although the data are sparse and unevenly sampled, the continuum flux density and the line flux over the 8 year observation period show very different characteristics (Figs. 3 and 4). The continuum flux has varied by a factor of ~ 50, while the Lyα line flux has remained nearly constant. We used two independent methods to test whether the emission-line flux is constant. In the first method, a reduced χ^2 test on the emission-line flux gives a $\chi^2 = 1.3$ for 12 degrees of freedom, indicating that the emission-line flux data are consistent with being constant. In the second method, in our line-fitting procedure (discussed in § 2) we kept all parameters of the Gaussian model constant and determined the reduced χ^2 of the fit for each spectrum. The constant model used the parameters derived from the 1992 FOS spectrum, which has the best S/N and spectral resolution. The reduced χ^2 of the constant model and the free Gaussian model were checked using an *F*-test. This test showed that the constant model and the free Gaussian model were comparable at the 95% level ($F = 1.1$ for a change of 2 degrees of freedom). We conclude that in 3C 279, although the observed continuum flux density has varied, the Lyα flux has remained essentially constant.

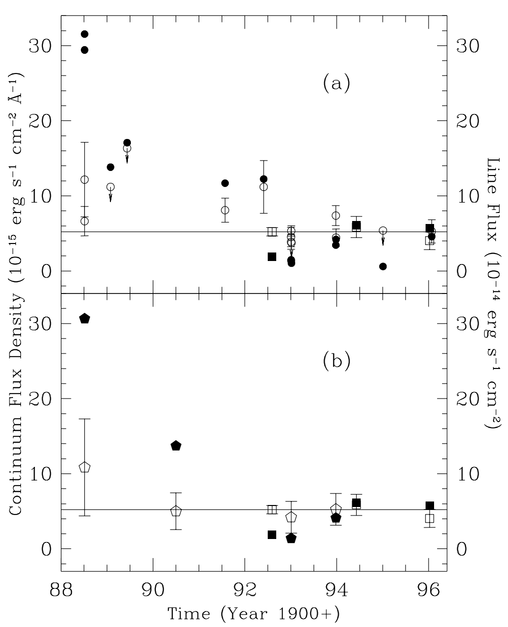

FIG. 3.—(*a*) The continuum flux density (*filled points*) and Lyα line flux (*open points*) of 3C 279 as a function of time. Over the 8 years of observations the source faded by a factor of ~ 50, followed by a slight increase at the most recent epoch. The *IUE* data are represented by circles and the *HST*/FOS data by squares. Error bars are smaller than the symbol if not indicated in the figure. (*b*) Same as (*a*), but for co-added *IUE* spectra (*pentagons*) and *HST*/FOS data (*squares*).

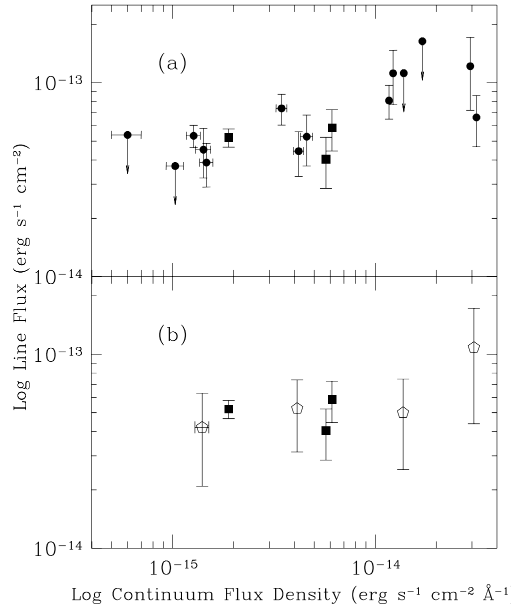

FIG. 4.—(*a*) The Lyα line flux of 3C 279 as a function of the continuum flux density (*circles*: *IUE*; *squares*: *HST*/FOS). (*b*) The Lyα line flux of 3C 279 as a function of the continuum flux density for the co-added spectra and the *HST*/FOS (*pentagons*: *IUE* co-added; *squares*: *HST*/FOS) Over a period of 8 years the continuum flux varies by a factor ~ 50 while the line flux remained nearly constant.

This trend between the continuum and line is similar to the case of 3C 273, where the Lyα varied little or not at all during a factor of 3 change in the UV continuum (Ulrich et al. 1993). Such a trend between the emission-line fluxes and the continuum was first noted by Sandage, Westphal, & Strittmatter (1966). The continuum and line variation in 3C 279 is in sharp contrast to that seen in Seyfert galaxies, where the continuum and line vary with similar amplitudes and in a correlated way (Koratkar & Gaskell 1991; Clavel et al. 1991; Peterson 1993; Reichert et al. 1994; Crenshaw et al. 1996; Wanders et al. 1997). This lack of Lyα variation is not just an effect of temporal sampling of the variability. In order to determine the effect of temporal sampling on the line variability, we compared our results with those of the much better understood case of the Seyfert galaxy NGC 5548, which shows a clear correlation ($r = 0.6$, $p \sim 99\%$) between Lyα and the UV continuum (Clavel et al. 1991; Korista et al. 1995), with a lag of ~ 10 days. In 1989, NGC 5548 was observed every 4 days for 8 months (Clavel et al. 1991). We selected 16 points at random from the 1989 NGC 5548 continuum and Lyα light curves. For these 16 points we determined the amount of variation in both the continuum and lines flux. The process was repeated 100 times. There was not a single 16 point sampling where the line flux was constant while the continuum flux varied as seen in 3C 279. This difference in the Lyα variability of blazars can be explained if the thermal continuum that primarily photoionizes the line-emitting gas is hidden by the variability of the beamed continuum in radio-loud AGN. This effect would be strongest in blazars, where the beamed component contribution dominates the observed continuum.

The Lyα equivalent width ($W_{Ly\alpha}$) of 3C 279 ranges between 1 and 45 Å (Fig. 5). These values of $W_{Ly\alpha}$ are smaller than those observed in normal quasars (Kinney, Rivolo, & Koratkar 1990; Cristiani & Vio 1990; Cheng & Fang 1987), where the thermal component, possibly the accretion disk, is the only source of ionizing radiation and observed continuum and gives rise to the observed $W_{Ly\alpha} \sim 100$ Å. In blazars there are two sources of ionizing radiation: (1) the beamed nonthermal radiation from the relativistic jet, and (2) the thermal component probably from an accretion disk. Thus, the observed continuum has contributions both from the disk and jet. If we assume that the beam is not contributing to ionizing the line-emitting gas, and only the thermal component is responsible for line emission, then the contribution of the beamed component to the observed continuum determines the strength of the equivalent width. The expected $W_{Ly\alpha}$ in blazars should be smaller than observed in normal quasars and should be anticorrelated with the contribution of the beamed component to the observed continuum (see Corbett et al. 1996). In 3C 279 we see this characteristic equivalent width trend (see Fig. 5). At low observed continuum levels, the $W_{Ly\alpha}$ becomes comparable (~ 100 Å) to other quasars when the beamed continuum contribution is ~ 2 times the accretion disk contribution, and at high observed continuum levels the beamed continuum contribution is ~ 30 times the accretion disk contribution. This model suggests that at low continuum levels we should see a change in UV continuum slope because of the increased contribution of the big blue bump associated with a accretion disk. At high continuum levels we should just see the synchrotron power-law slope. Such a change in the UV slope of 3C 279 has been noted by Pian et al. (1997).

One of the models for the production of γ-ray emission in blazars is Compton upscattering of ambient Lyα line photons (Sikora, Begelman, & Rees 1994). Variability of

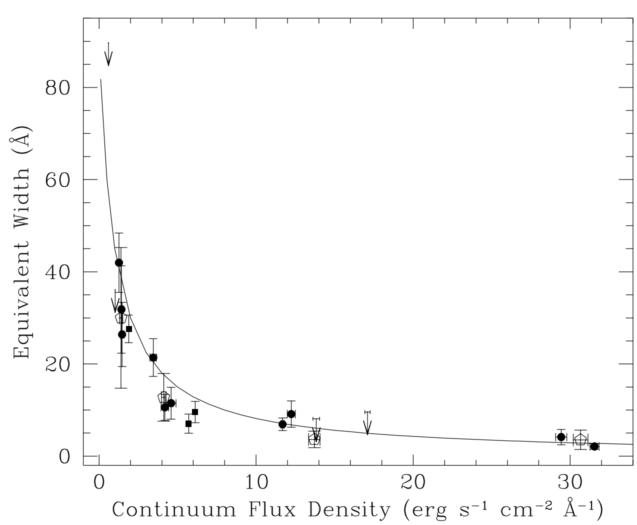

FIG. 5.—The Lyα equivalent width as a function of the continuum flux density (*circles*, *IUE* individual; *pentagons*, *IUE* co-added; *squares*, *HST*/FOS). Such a decline in equivalent width is possible if the line is primarily ionized by the thermal component, but the flux in the observed continuum has varying contributions from the beamed continuum. The solid line represents the variation in equivalent width for a constant line intensity and a varying beamed continuum.

γ-rays could therefore be caused by changes in the Lyα intensity or in the energetic electrons of the jet. The γ-rays would vary linearly with Lyα flux and/or quadratically with respect to synchrotron emission depending on the direction of the jet electrons. If some of the Lyα flux increases in response to the beamed continuum (Ghisellini & Madau 1996), then the γ-ray flux could increase even more than the square of the observed UV synchrotron flux. A strong correlation between UV and γ-ray flux has been observed in 3C 279 (Maraschi et al. 1994; Wehrle et al. 1997), indicating that the beamed continuum could be ionizing some of the line-emitting gas. Our present analysis suggests that γ-ray variability must be caused by variations in the jet rather than the external Lyα photons. The present data do not allow us to determine the contribution of jet synchrotron emission to photoionizing some of the Lyα emission clouds. If the beamed continuum does ionize some of the line-emitting gas, we should see rapid variations in the emission-line profile. The nature of the variations would depend on the kinematic structure of the line-emitting gas. Our *IUE* data do not have high enough spectral resolution or S/N to allow us to decompose the line core and wings but the Lyα line profile appears symmetric, as it does in the FOS 1992 spectrum (Netzer et al. 1994). The 1994 and 1996 FOS spectra show intrinsic absorption and do not have sufficient S/N to determine accurately the line profile variations. Simultaneous monitoring of 3C 279 in both the UV and γ-ray would allow us to study continuum and emission-line profile variability, and then unambiguously select the correct inverse Compton model for γ-ray production.

4. CONCLUSIONS

Our analysis of the archival *IUE* and *HST*/FOS observations of 3C 279 over a period of 8 years shows that although the continuum has varied by large amplitude, the Lyα flux has remained essentially constant. This suggests that the beamed continuum is not the dominant source of photoionization of the broad-line clouds, which are instead likely to be powered by a thermal component underlying the beamed continuum.

The strong γ-ray emission from 3C 279 may be due to Compton scattering of the Lyα line photons. In this case, the large amplitude of the γ-ray variability must be due to changes in the energy distribution of electrons in the jet, rather than changes in the external photon field. This implies that γ-rays will change as the square of the synchrotron flux, or perhaps even more if the beamed continuum ionizes line-emitting gas lying close to the jet axis (Ghisellini & Madau 1996). High-quality line profile observations are necessary to test this model further.

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