THE OPTICAL–ULTRAVIOLET–γ-RAY SPECTRUM OF 3C 279

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ABSTRACT

We have obtained spectroscopy of the violently variable quasar 3C 279, simultaneous with γ-ray observations, in 1992 April. Our combined optical (McDonald Observatory and CTIO) and ultraviolet (*HST*) observations, made when the source was faint, show a very steep power-law continuum ($F_\nu \propto \nu^{-1.95}$), and strong broad emission lines. This is the first time that the broad ultraviolet lines of this object have been measured, and we note several unusual properties of the spectrum. In particular, the profiles of C IV λ1549 and Mg II λ2798 are asymmetric, with very strong red wings, in contrast to the symmetric profile of Lyα C III] λ1909, and possibly Hβ. The observed asymmetry cannot be explained by a simple outflow associated with the eruption of the source. In addition, the C IV λ1549/Lyα and C III] λ1909/Lyα line intensity ratios are the largest we have observed in our *HST* sample of more than 30 radio-loud quasars, even though the C III] λ1909/C IV λ1549 ratio is quite typical. 3C 279 was observed in the γ-ray region by EGRET at the same time as our optical-ultraviolet observations. The extrapolated ultraviolet continuum falls nine orders of magnitude below the γ-ray point and we show that this, combined with the optical UV continuum slope, is enough to rule out several synchrotron–self-Compton models suggested to explain the multiwavelength spectra of blazars.
blazars.

Subject headings: galaxies: active — gamma rays: observations — quasars: individual (3C 279) —
radiation mechanisms: nonthermal — ultraviolet: galaxies

1. INTRODUCTION

The optically violently variable (OVV) quasar 3C 279 ($z = 0.536$) is one of the best studied objects of this subclass of AGNs (sometimes referred to as blazars), showing large continuum variations at all wavelengths, from radio to γ-rays. The optical variability of this object has been monitored on very long (Eachut & Liller 1979) and short (e.g., Webb et al. 1990) timescales and the reported *B* magnitude covers the range 11.3–18. This OVV has been the subject of a very extensive multiwavelength study during 1987–1990 and in 1992 November (see Makino et al. 1991; Makino, Fink, & Clavel 1992; Urry 1994 for reviews and references). The main findings of the above campaigns are the correlated X-ray (*Ginga*) and millimeter radio--wave variability, the flat X-ray spectrum, and the short optical variability timescale compared with other wavelength bands. The spectral index $\alpha \sim 0.6$–0.7 from 2–10 keV ($F_\nu \propto \nu^{-\alpha}$), is flatter than is typical for X-ray spectra of other OVVs and BL Lac objects (Makino et al. 1989).

Recently there has been renewed interest in 3C 279 because of the large γ-ray outburst discovered by EGRET, the Energetic Gamma-Ray Experiment Telescope on board *CGRO* (the *Compton Gamma-Ray Observatory*). Large flux variations and high-energy (≥ 1 GeV) radiation have been reported. The γ-ray luminosity of the object during the first month of EGRET observations (Bertsch et al. 1991; Hartman et al. 1992a, b) exceeded the total optical-ultraviolet-X-ray flux reported in any previous observation. The γ-ray behavior has been followed throughout 1991 and 1992, and shows a large flux decrease starting around 1991 October (Kniffen et al. 1993).

Despite the great interest in this object, there is little information about its optical-ultraviolet emission line spectrum. This is mainly the result of the limited sensitivity of past ultraviolet instruments and the strong nonthermal continuum. When the source is bright, the 45 cm telescope of the *IUE Observatory* can be used to measure continuum fluxes. However, the equivalent widths of the ultraviolet lines during such phases are very small and the lines are probably not detectable (e.g., Shrader et al. 1994). The low brightness phases show very weak continuum and the overall signal-to-noise is too low, even for the ~ 7 hr exposure of a full *IUE* shift.

Ground-based studies during bright phases are not much more successful (e.g., Peterson, Wagner, & Korista 1988; Shrader et al. 1994; Bonnell, Vestrand & Stacy, 1994).

In this paper we report on new spectroscopic observations of 3C 279 using the *Hubble Space Telescope* (*HST*) and several ground-based telescopes, during 1992 April. Our observations were made when the object was at a local flux minimum and are the first to show the emission-line spectrum and the combined optical-ultraviolet continuum at this phase. We were fortunate to have an EGRET measurement taken almost simultaneously with our spectroscopy, as the multiwavelength spectrum is of great interest for the modeling of such sources. In § 2 we report on our observations and compare them with the γ-ray measurements. In § 3 we show and discuss the emission-line spectrum, with emphasis on the unusual line profiles and address the question of the synchrotron self-Compton (SSC) model in light of the new observations.

2. OPTICAL, ULTRAVIOLET, AND γ-RAY OBSERVATIONS

Observations of 3C 279 have been made as part of a long-term project to study the multiwavelength properties of a sample of radio-loud quasars. The sample is described in our first paper addressing the narrow-line spectra of high-luminosity AGNs (Wills et al. 1993) and in the *HST* data paper (Wills et al. 1994). We are obtaining simultaneous ground-based and space-based spectroscopy for ~ 50 radio-loud quasars to study various correlations involving emission lines and continua across the electromagnetic spectrum. So far we have secured data for some 30 objects, covering rest wavelengths from below Lyα to beyond 8000 Å. Wills et al. (1993, 1994) give information regarding the instrument set-ups, calibration procedure etc. Here we address only the 1992 observations pertaining to 3C 279.

Our observations took place in 1992 April, when 3C 279 was at a local flux minimum, having declined from a higher state in 1992 February (our own results, to be reported in a future paper) and before rising to another peak in 1992 June (Hartman et al. 1993). The *R* magnitude at the time of our observations was ~ 15.8. A log of the spectroscopy observations is given in Table 1. Some observations were obtained during clear weather conditions with large apertures; thus spectrophotometric accuracy of better than 5% was achieved.

The spectra of UT 1992 April 7 and 13 were ~ 15% above the *HST* spectra and the far red spectrum of UT 1992 April 9. This difference lies outside the expected flux calibration uncertainties, indicating real variability during the period of the UV to infrared spectroscopy.

Two observations were made by EGRET in 1992 April. (For a description of the instrument and data reduction, with reference to previous observations of this source, see Kniffen et al. 1993). The γ-ray flux level measured during the first EGRET observation (1992 April 2–9) is about a factor of 5 below the maximum flux of 1991 June, and similar to the level observed in 1991 October. The second EGRET observation (1992 April 10–16) gives an upper limit of ~ 10% of the maximum 1991 June flux level. We note that the April 2–9 point is only a 1.5 σ detection and so is not very certain. It is possible that the γ-ray flux of 3C 279 was declining during the 1992 April observations, falling below the instrumental threshold. Figure 1 shows, in an insert, the EGRET flux density on the same scale as the optical-UV observations. (The 1 GeV flux density was derived by assuming $\alpha \sim 1.0$ in the γ-ray region; see Kniffen et al. 1993).

3. RESULTS AND DISCUSSION

3.1. *Broad Emission Lines*

Our spectroscopic observations are the first with adequate signal-to-noise ratio and faint enough continuum to enable a careful study of the strong optical and ultraviolet emission lines. Figure 2 compares the profiles of Lyα, C IV $\lambda1549$, C III] $\lambda1909$, Mg II $\lambda2798$, and Hβ. We have decreased the FOS wavelengths by 1.2 Å so that on average Galactic absorption lines (Mg II $\lambda2798$, Fe II $\lambda\lambda2600$, 2585, and 2343) are at their nominal rest wavelengths. The uncertainties in this wavelength scale are probably less than 100 km s^{-1}. The rest wavelength scale is based on a redshift of 0.5356 (not corrected to heliocentric) determined from the narrow [O III] $\lambda5007$ line. The redshifts of the peaks of other strong lines are consistent with this. Some emission-line properties are summarized in Table 2.

The most striking aspect of the line profiles are the strong red wing to C IV $\lambda1549$ and Mg II $\lambda2798$. We detect no trace of it in Lyα and the noisier C III] $\lambda1909$ and Hβ profiles do not show a red wing either. We know of no other high-luminosity AGN with such extreme behavior, although there are less-

TABLE 1
OBSERVING LOG

UT Date	Observatory Telescope	Instrument Detector	Wavelength Range (Å)	Resolution (km s^{-1})	Aperture Slit	Cloud/Seeing
1992 Apr 9	STcI *HST*	FOS[a] Digicon	1573–4784	450	4".3 × 4".3	Photometric
1992 Apr 7	McDonald 2.7 m	LCS[b] CRAF[c]	4584–7336	590–370	8	Clear/2"
1992 Apr 9	McDonald 2.7 m	LCS[b] CRAF[c]	7100–9850	340–240	2	Clear/1"–2"
1992 Apr 9	McDonald 2.7 m	LCS[b] CRAF[c]	7100–9850	390–270	6	Clear?/1"–2"
1992 Apr 13	CTIO 4 m	RCS[d] Reticonl	3007–7274	700–1400	3.3	Photometric

[a] FOS: The Faint Object Spectrograph, using high-resolution gratings G190, G270, and G400.
[b] LCS: The Large Cassegrain Spectrograph.
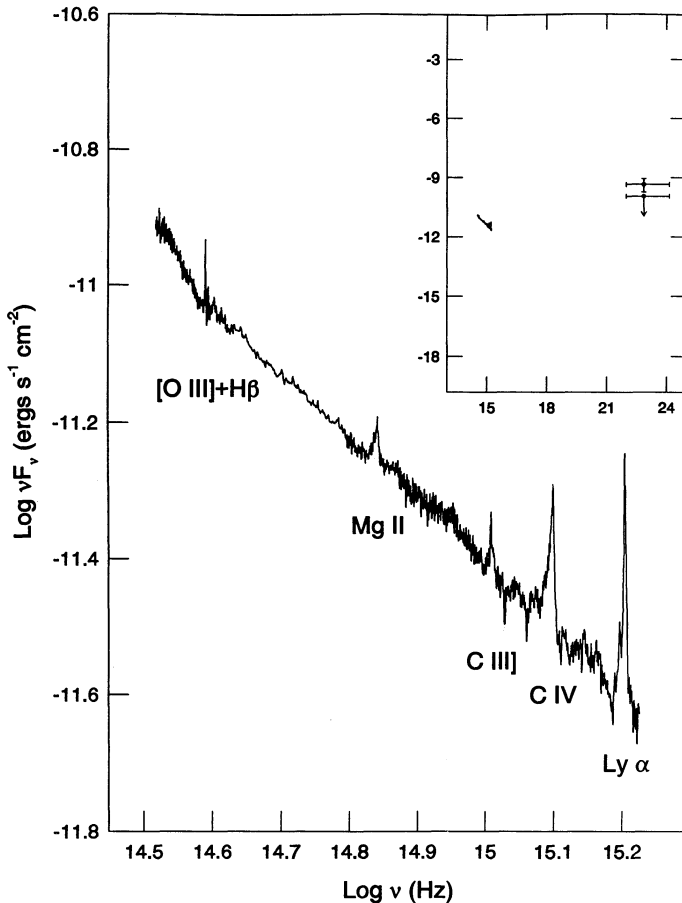[c] CRAF: A thick CCD chip developed for the CRAF-Cassini mission.
[d] RC Spectrograph.

FIG. 1.—The 1992 April multiwavelength spectrum of 3C 279. The insert shows the combined optical-ultraviolet-γ-ray spectrum with the EGRET points from Kniffen et al. (1993), with the flux density uncertainty and the EGRET energy band indicated. A reddening correction corresponding to $E(B - V) = 0.015$ has been applied to the optical-ultraviolet data (Burstein & Heiles 1992).

extreme examples (Corbin 1991). The extreme red wing in 3C 279 may be related to the extreme γ-ray luminosity in the same way that Hβ red asymmetries have been noted to correlate with X-ray luminosity (Corbin 1993).

With respect to its X-ray luminosity, extended radio luminosity, average optical luminosity, and redshift, 3C 279 is quite typical of quasars in our *HST* sample and so this sample provides a useful comparison. Some other OVV (radio core-
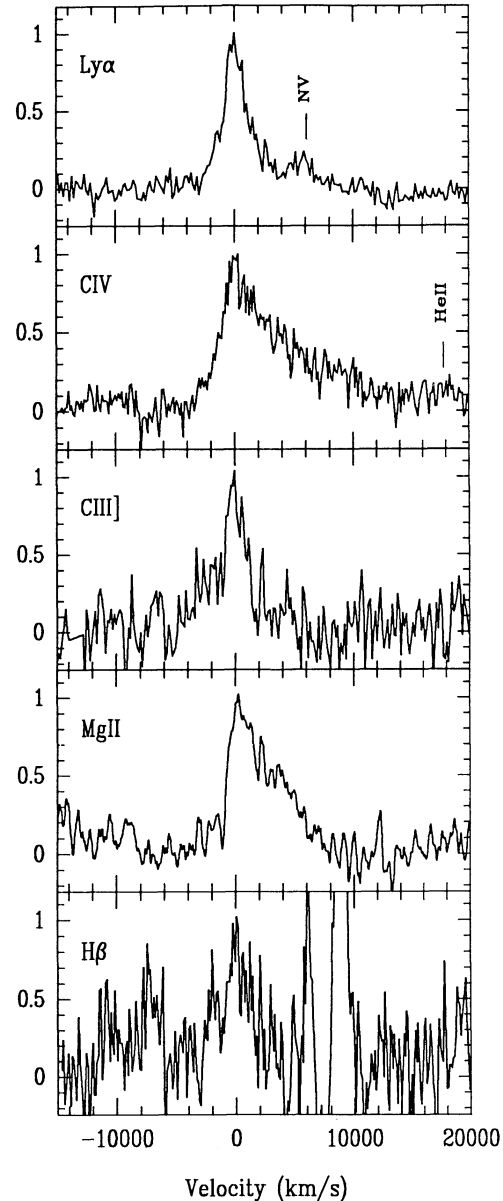

FIG. 2.—Observed emission line profiles in 3C 279, normalized to the line peak intensity. Note the very strong red wings of C IV λ1549 and Mg II λ2798 that are not present in the Lyα and the C III] λ1909 profiles. The zero of the velocity scale is defined by the redshift of [O III] λ5007.

TABLE 2

EMISSION-LINE MEASUREMENTS

Line	Peak Redshift[a]	Intensity[b]	Equivalent Width	FWHM (km s^{-1})
Lyα	0.5357	3.35 ± 0.18	26.0 ± 1.4	2150 ± 282
C IV λ1549	0.5354	3.64 ± 0.14	28.0 ± 1.1	6020 ± 488
C III] λ1909	0.5355	1.10 ± 0.12	8.5 ± 0.96	3080 ± 808
Mg II λ2798	0.5366	1.8 ± 0.30	14.9 ± 2.5	3220 ± 1500
Hβ	0.536	0.80 ± 0.20	5.0 ± 2.0	4937 ± 800
[O III] λ5007	0.5356	0.61 ± 0.08	5.41 ± 1.5	683 ± 50

[a] The assumed rest wavelength of C IV λ1549 and Mg II λ2798 is the equally weighted mean of the doublet wavelengths.

[b] The line strengths, in units of 10^{-14} ergs s^{-1} cm^{-2}, are determined using a local power-law continuum and exclude contributions from the blended lines N V λ1240, He II λ1640, Al III λ1859, etc., determined by a Gaussian fitting method.

dominant) quasars in our sample show red wings on their C IV $\lambda1549$ profiles, but within a given spectrum the different emission lines' profiles are more similar. Recently we found one other object that is quite similar to 3C 279: 4C 55.17, for which there is a marked red wing to C IV $\lambda1549$ that is weaker in Lyα. We note that the 3C 279 Lyα line is among the narrowest (FWHM) in our sample. The C IV $\lambda1549$ line width is no broader than typical despite the strong red wing. The line equivalent widths of 3C 279 are the smallest in our sample, even compared with other core-dominant quasars. A comparison of the line ratios shows that the C IV $\lambda1549$/Lyα line ratio is anomalously large (~ 1), and Lyα/C III] $\lambda1909$ is the smallest in the sample (so far), indicating that Lyα is perhaps anomalously weak. The C IV $\lambda1549$/C III] $\lambda1909$ ratio is quite typical.

A naive interpretation of the OVV spectrum involves an outburst resulting in a source of continuum radiation that is highly beamed toward us. Since beaming is indicated by the nonthermal nature of the optical-ultraviolet continuum, and the large fluctuations in the X-ray and γ-ray flux, it is possible that the ionizing continuum is also beamed in our direction. Thus material along the line of sight will be affected most by the enhanced continuum and line radiation from this region (which is in rest and therefore emitting unbeamed radiation) will be enhanced. While this has been suggested as a major source of observed line variability in OVVs (e.g., Bregman et al. 1986; Perez, Penston, & Moles 1989) we are not yet in a position to comment on it in detail since we have not investigated the line intensity at brighter continuum phases. However, a preliminary inspection of some of our other spectra suggest that the line equivalent width during bright continuum phases is smaller than presented in Table 2, in contradiction to this picture.

The following is a simplified model of the gas distribution in 3C 279, based on current ideas about core-dominated quasars and OVVs. Assume a broad-line region (BLR) that is roughly spherical or extends along the beam direction (a BLR flattened in a plane perpendicular to the beam, which has been suggested for quasars, cannot explain the observed behavior). The BLR gas is excited mainly along the beam, and large amplitude line intensity variations are expected. The strong observed red wing of C IV $\lambda1549$ is suggestive of material falling to the center on the observer's side of the source, or outflow on the far side with line radiation emitted toward the ionizing source from regions that are optically thick. This material must have an unusually large C IV $\lambda1549$/Lyα intensity ratio (>5), since no Lyα far red wing is observed. In this case, the symmetric Lyα and C III] $\lambda1909$ lines come from regions not exposed to the beamed ionizing radiation. The very large C IV $\lambda1549$/Lyα ratio in the red-wing velocity band is incompatible with any photoionization model known to us. Moreover, the red wing of Mg II $\lambda2798$ suggests that the ionization parameter of the red-wing material is not large and the absence of strong red wings to the hydrogen lines is unexplained. There is also an indication that radiation pressure acceleration does not play an important role since an extended blue wing is expected in such cases. The only conclusion we can draw is that the BLR gas in this object is highly stratified.

3.2. The Nonthermal Continuum

Figure 1 shows the combined optical-ultraviolet spectrum of 1992 April, covering the rest wavelength range 1024–6200 Å, after scaling the spectra of UT 1992 April 7 and 9 to match the

other spectra. In the optical-ultraviolet region it can be fitted quite well by a power law $F_\nu \propto \nu^{-\alpha}$ with $\alpha = 1.95 \pm 0.05$. This is similar to slopes reported previously. Shrader et al. (1994) and Bonnell et al. (1994) suggested a possible correlation of the flux level and the continuum slope such that the continuum is steeper when the source is fainter. The Shrader's et al. 1992 June observation, made when the overall flux level was about a factor of 6 higher, gives $\alpha = 1.74$. Comparison with our data supports this idea but other measurements, using broad-band photometry (Shrader et al. 1994 and references therein) are inconclusive on this point. The inspection of the more complete IUE data set, presented in Edelson et al. (1992), gives some support to this claim (see the LWP data there) but it is not at all clear how general is this trend.

The extrapolation of our optical-UV continuum to the $E > 100$ MeV EGRET range, combined with the observed continuum slope, gives a flux level that is a whole nine orders of magnitude below the observed γ-ray flux. An alternative way to demonstrate this vast mismatch is note that combining the 3000 Å point with the 100 MeV point by a single power-law continuum requires an energy slope of ~0.82, while the observed slope is 1.95. This huge mismatch implies the existence of an additional component that dominates the emission at energies beyond a few eV.

The need for an additional component at high energies is not new since for AGNs in general, the extension of the optical-UV spectrum falls below the observed X-ray flux at energies greater than a few keV. Specifically, in radio-quiet and lobe-dominated radio-loud objects, it is likely that the 1000–6000 Å part of the spectrum (sometimes named the "Blue Bump") is mostly due to emission from an accretion disk, or another thermal source, with characteristic energy of a few eV. The need for an additional component is indicated by the fact that, in most objects, the X-ray flux lies above the extrapolation of the high-energy tail of this thermal component. A similar component is also needed to account for the >1 keV emission in core-dominated radio-cloud AGNs and also in blazars, even though in this latter class it is considered that the entire radio to UV emission is dominated by nonthermal processes, in particular synchrotron emission from a population of relativistic electrons. Most blazar models invoke, in addition to synchrotron emission, high-energy radiation by inverse Compton scattering of the synchrotron photons (SSC; see Jones, O'Dell, and Stein 1974). It is this latter process, rather than the synchrotron emission, that is expected to dominate the emission at very high energies, giving rise to the 3–10 keV flux observed by Ginga and the >100 MeV γ-ray flux observed by EGRET.

While our optical-UV observations of 3C 279 are consistent with a pure power-law continuum, and no thermal bump, they are also consistent with a weak bump with emission lines of typical equivalent width and a steepening synchrotron spectrum (this steepening is often observed in blazars when dominated by the nonthermal component). We shall proceed under the assumption of pure nonthermal continuum, keeping in mind the possibility that this may apply only when the source is bright.

If we identify the optical-UV spectrum with synchrotron radiation by a population of relativistic electrons, and the EGRET γ-rays as the inverse Compton-scattered radiation associated with the same electrons, the difference between the optical-UV and γ-ray slopes is disconcerting since, according to the simplest models, i.e., those of a fixed homogeneous distribution of relativistic electrons and a uniform average mag-

netic field, the spectral indices of these two components should be identical.

It may be argued that a much flatter radio-IR continuum is present and may be the missing, low-frequency component. While we have no direct evidence to rule this out (due to lack of observations) we find it unrealistic since in such a case, the optical-UV continuum should represent the fall-off of this hypothetical flat component. Our observations (Fig. 1) do not look at all like an exponential drop and are, in fact, perfectly consistent with a power-law over a large-range (factor of 5) in frequency.

More realistic homogeneous models (i.e., the equivalent of a single moving blob of fixed electron distribution and uniform magnetic field) should actually provide the relativistic electron injection rate rather than their distribution function (see Kazanas 1984) and should determine the latter from the balance between the electron injection and their losses. Within such models, it is very difficult to reconcile the observed steep optical-UV slope of 3C 279 and the fact that its bolometric emission is dominated by the γ-rays. The observed dominance of the inverse Compton emission suggests, if anything, that almost independent of the spectrum of the injected electrons, the upscattering of the synchrotron photons to produce the observed Compton luminosity should result in a synchrotron spectrum much flatter than that observed (see, e.g., Zdziarski & Lamb 1986). Thus, in this type of model, it is *the ratio* of the γ-ray to optical-UV luminosity, rather than the γ-ray slope, that is the most critical observed property, and our observations of 3C 279 are the first to provide this information on any blazar. Our measured γ-ray–to-optical luminosity rules out the simple, homogeneous, self-consistent model of the nonthermal continuum of 3C 279.

The resolution to this problem may lie in the fact that neither the electron density nor the average magnetic field are uniform in space, but are distributed, presumably with power law form, over several orders of magnitude in radius (inhomogeneous synchrotron models; Marscher 1977; Band & Grindlay 1985). These models, because of the additional freedom, fare better in fitting the optical-UV and γ-ray spectra. They achieve this by the superposition of a large number of components with judiciously chosen magnetic field and electron normalization and slopes that are allowed to depend on radius. These are physically motivated by the fact that the relativistic jet models that are generally thought responsible to the blazar emission (Königl 1981), naturally lead to such inhomogeneous distributions. The appearance of a single optical-UV power-law optical-UV continuum in those models is the result of superposition of many exponentially decaying synchrotron sources (e.g., Maraschi, Ghisellini, & Celotti 1992, Fig. 2). Such a good agreement with a power-law spectrum cannot extend over a very large frequency range and observations like ours can be used to set limits on the validity of such models.

In conclusion, the observed well-defined, single-slope, power-law optical-UV continuum of 3C 279 along with the simultaneous γ-ray measurements provide very stringent constraints for blazar models. While it is easy to see that the simplest of them are incompatible with such observations, we would like to defer to future work the issue of whether the more complicated ones could provide good fits to these data. What we would like to stress is the importance of such high-quality broad-band measurements in constraining and eventually understanding the details of the blazar emission mechanism.

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