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HIGH-RATE SPECTROSCOPIC ACTIVE GALACTIC NUCLEUS MONITORING AT THE WISE OBSERVATORY. I. MARKARIAN 279

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ABSTRACT

We monitored spectrophotometrically a sample of AGNs, and achieved a temporal sampling rate of once every 3–4 days, over a period of 5–7 months. By observing each object simultaneously with a nearby field star, in a long-slit spectroscopy mode, we obtained accurate flux measurements even during bad weather and full moon. In this paper, the first in a series, we describe our observational technique and reduction procedure in general, and discuss our results for the Seyfert 1 galaxy Mrk 279. This object brightened by 20%–50% in Hα, Hβ, and the optical continuum during the period of observation. The high sampling rate and small error allow the determination, through cross-correlation, of the lag in the emission-line response to the continuum brightening. A lag of 12 days is observed. Using Monte Carlo simulations, we estimate the size of the broad-line region (BLR) to be 12 ± 3 light days in this object and find that the results rule out, at the 95% significance level, a BLR of 21 light-days or larger. This result is in conflict with the "standard" photoionization model of AGNs, which predicts a BLR size larger by an order of magnitude.

Subject headings: galaxies: individual (Mrk 279) — galaxies: photometry — galaxies: Seyfert — spectrophotometry

I. INTRODUCTION

Since the discovery of correlated continuum and emission line variability in active galactic nuclei (AGNs), it has been apparent that comparison of continuum and emission-line light curves may enable the determination of the broad-line region's (BLR) dimensions and structure (Bahcall, Kozlovsky and Salpeter 1972; Blandford and McKee 1982; see Peterson 1988 for a review). Intensive observations to this end were carried out during the past decade, concentrating on a number of Seyfert 1 galaxies (e.g., Antonucci and Cohen 1983; Peterson *et al.* 1985; Clavel *et al.* 1987; Clavel, Wamsteker, and Glass 1989; Wamsteker *et al.* 1989; Clavel, Wamsteker, and Ulrich 1989). Gaskell and Sparke (1986) analyzed some of these observations using the cross-correlation technique to determine the time lag between the lines and the continuum. They obtained results seemingly in conflict with the standard photoionization model of AGNs (Davidson and Netzer 1979), their BLR dimensions being one to two orders of magnitude too small.

The data and the uncertainty of these results were further analyzed by Gaskell and Peterson (1987), Edelson and Krolik (1988), Alloin, Boisson, and Pelat (1988), Maoz and Netzer (1989), Peterson and Cota (1988), and Peterson and Gaskell (1989). In particular, Maoz and Netzer (1989) used Monte Carlo simulations to determine the significance of the variability results under a range of model assumptions. They showed that the significance of the results in disproving the standard model was model dependent and, in any case, not high. Furthermore, they showed that due to the short variability time scales and emission-line response times being considered, greatly improved sampling frequency and measurement accuracy are needed in order to obtain unambiguous results.

We carried out such observations at the Wise Observatory between 1987 December and 1988 July. A sample of 14 AGNs was monitored spectrophotometrically every 3–4 nights, on average, during this period. This paper is the first in a series in which we present the results of our project. We discuss here the observing method and the data reduction and analysis and describe the line and continuum variations of the Seyfert galaxy Mrk 279.

Mrk 279 is a typical, fairly luminous Seyfert 1. Its optical spectrum has been studied by Osterbrock and Shuder (1982), who also noted it to be variable by $\sim$20% in Hβ and the continuum over less than a year, with Hα constant. Peterson, Crenshaw, and Meyers (1985) followed up on these observations and detected a 25% variation in the optical continuum with a 60% change in Hβ over 14 months. Chapman, Geller, and Huchra (1985) found ultraviolet continuum variations of 60% and possible variations of 15%–20% in Lyα and C IV λ1549 flux within 150 days. X-ray variability by a factor of 2–3 over several years was reported by Reichert *et al.* (1985). Edelson and Malkan (1987) found the far-infrared flux to be constant. Apart from these observations, no systematic monitoring of this galaxy has yet been carried out.

Section II describes our observations. In § III we discuss the data reduction, the spectral measurements and the error analysis. In § IV the results are analyzed, the size of the BLR of Mrk 279 is estimated and the implications are briefly discussed. Section V summarizes our results.

II. OBSERVATIONS

The monitoring of AGNs started in December of 1987, with the aim of covering a large number of objects (14) with a high sampling rate (intervals of a few days) over a period of 7 months and through all phases of the moon.

Spectra were obtained with the Boller and Chivens spectrograph at the Cassegrain focus of the Wise Observatory 1 m telescope. The detector was a thinned RCA 512 × 320 pixel CCD. A 300 line mm^{-1} grating blazed for first order at 7620 Å yielded spectra between 4600–7000 Å with a resolution of $\sim$10 Å (2 pixels). The cross-dispersion scale was 2\".8 per pixel. A GG 400 filter was used to remove higher order contamination.

The observing procedure was as follows:

1. A long (8′) and wide (20″) slit was used.
2. For each AGN observed, the slit was oriented so that a nearby field star, serving as a comparison standard, could be observed simultaneously. The presence of a suitable star within 5′ of the object was one of the criteria in choosing our sample.
3. Two consecutive 15 or 20 minute exposures were taken on each successful observing run.
4. On clear nights standard stars (Stone 1977) were also observed in order to calibrate the comparison stars.
5. To obtain wavelength calibration, He-Ar arc spectra were taken several times each night.

By observing the object, comparison star, and sky under exactly the same conditions we were able, in principle, to achieve photometric accuracy even when observing at high air masses and with adverse weather. Such conditions are unavoidable when attempting to obtain ground-based data with the necessary temporal coverage. (In § III we show that we indeed obtained very high accuracy in practice). The large aperture protected against the systematic errors common in spectrophotometry of Seyfert galaxies and outlined by Peterson (1988), albeit at the price of larger sky and galactic continuum contributions to the resulting spectrum. In the subsequent data reduction, the ratio between the galactic and the comparison-star spectrum in the two consecutive exposures was checked, and the data were discarded if the ratio was not identical to within 3%. (In practice, this rarely happened).

A potential drawback of our method is the possibility that the comparison star chosen is variable. We can partially check this by using the observations of standard stars on photometric nights. This is reexamined later, in § IV*a*.

This setup (small telescope, low-dispersion, large aperture, short exposures) gives low-resolution, low S/N spectra. However, as we will show below, it suffices to determine well the optical continuum flux density and the total flux in the two main optical broad emission lines, Hα and Hβ.

For Mrk 279, we used as a comparison standard the 13th magnitude G-type star 2′ west and 3′ north of the galaxy. The dates of our successful observations of this galaxy appear in Table 1. We observed it on 45 occasions during a 156 day period. Six epochs were discarded at the preliminary reduction stage for not passing the criterion of identity between the two consecutive exposures, or due to unacceptably low S/N. We thus have 39 successful observations, or an average sampling interval of 4 days. To our knowledge, no other Seyfert galaxy has been observed this frequently.

III. REDUCTION

Data reduction was carried out using the VISTA image processing package developed at, and kindly supplied by, the Lick Observatory. The raw CCD images were bias-subtracted but not flat-field corrected, due to difficulties in uniformly illuminating the detector in its spectroscopic mode. However, analysis of twilight sky images taken in the *B*, *V*, and *R* bands with the same camera in its imaging mode shows that the overall sensitivity across the detector changes by less than 2%. We also tested for vignetting in the cross-dispersion direction by examining the spectrum of a star at various positions along the slit, with negative results. Furthermore, the constraint of centering both the object and the comparison star in an 8′ long slit guarantees that their respective spectra will always be approximately on the same rows on the chip (e.g., the spectra of Mrk 279 fall within a range of 40 rows in all 39 observations; excluding two extreme cases, the range is only 25 rows). Pixel-to-pixel variations are averaged out in the spectrum extraction process. Thus our lack of flat-field correction should not seriously affect the results. This is reexamined in our error analysis below. The only apparent detrimental effect is a fringing in the far red part of the spectrum which is, in any case, unsuitable for our purpose due to the presence there of the atmospheric B band.

Cosmic-ray events were removed by replacing pixels with counts deviating largely from the median of their surrounding pixels by the median. The spectra of the galaxy and the comparison star were then extracted by summing counts along 10 rows (28″) in the spatial direction and subtracting the night sky at each column. The night sky spectrum was determined by averaging several sky rows adjacent to each spectrum and centered on it.

The star and galaxy spectra in the two consecutive exposures were compared as described above, and added if identical. The spectra were then wavelength calibrated and interpolated to a linear wavelength scale. The comparison star spectrum was median filtered to remove all noise and absorption lines. Absolute flux calibration of the comparison star was obtained from the combined observations of standard stars on photometric nights, from which a mean atmospheric extinction for Wise Observatory was also obtained. This flux calibrated comparison-star spectrum was then used to flux calibrate the galaxy spectra. Thus, although the accuracy of the absolute flux scale is typical of standard spectrophotometry, the internal calibration, relative to the local standard, is highly accurate, as we show below.

In order to determine well the spectrum of Mrk 279, an average spectrum having high S/N (of ~ 35 per spectral element) was constructed by adding all the best S/N (typically 10–15 per spectral element) calibrated spectra taken between February and April. Analysis of these spectra showed that the galaxy had varied little during this period. The [O III]$\lambda\lambda$4959, 5007 lines were used to align the spectra in wavelength before adding (a shift of two pixels, at most, was needed). The wavelength limits for the integration of Hα and Hβ and the best continuum bands free of nuclear emissions and stellar absorptions were determined from the average spectrum.

For each spectrum, we measured the mean continuum flux density in four spectral bands: 4630–4730 Å, 5380–5580 Å, 5950–6150 Å, and 6325–6425 Å (rest wavelengths). The continuum underlying Hβ was subtracted by assuming it to be a straight line in F_λ between the first two bands. The Hβ flux was found by integrating from 4810 Å to 4910 Å. This is not the total Hβ flux as it excludes part of the wings of the line. We found from experiment that such an exclusion is necessary, due to the noise that the inclusion of low-lying wings and improperly subtracted [O III]$\lambda\lambda$4959, 5007 residuals would introduce into the data. Nevertheless, the integrated flux includes most ($\sim 70\%$) of the line, which is what concerns us as we are foremost interested in the region which emits the bulk of the line.

As for Hα, part of its red wing and the continuum redwards of it are redshifted into the atmospheric B band. The continuum underlying Hα was therefore set by extrapolating the continuum measured in the last band at a constant $F\lambda$ level. The Hα intensity was integrated from 6440 to 6635 Å (i.e., excluding some of the red wing). Due to our low resolution, no attempt was made to remove the [N II]$\lambda\lambda$6548, 6583 and Fe II lines, or the narrow components from Hα and Hβ, nor the stellar contribution from the continuum.

TABLE 1

LINE AND CONTINUUM MEASUREMENTS OF MRK 279 IN 1988

Date	Day	4630-4730A	5380-5580A	5950-6150A	6325-6425A	$H\beta$	$H\alpha$
Feb14	1	58.3±2.2	55.2±1.8	56.3±1.8	59.3±2.0	23.0±1.9	126±4
Feb19	6	57.8±2.3	56.1±1.8	58.0±1.9	60.4±2.0	22.1±1.8	115±3
Mar 8	24	61.1±2.6	61.8±2.2	60.7±2.1	63.8±3.4	19.7±3.1	113±6
Mar11	27	56.5±2.2	55.6±1.8	59.2±2.1	55.2±2.6	22.1±2.1	116±5
Mar14*	30	60.5±2.1	55.4±1.9	55.7±2.0	58.2±3.7	19.0±1.1	106±7
Mar18	34	56.9±2.0	54.9±1.8	59.3±2.0	61.6±2.4	19.2±1.9	108±4
Mar24	40	60.8±2.7	55.5±1.8	59.2±2.0	56.4±2.1	21.2±3.1	112±4
Mar27	43	60.6±2.1	57.6±1.9	60.2±1.9	58.4±2.0	21.1±1.7	113±3
Mar31	47	60.4±2.7	56.5±1.9	59.2±2.0	60.8±2.2	29.6±2.9	108±4
Apr14*	61	59.6±2.3	58.5±1.9	58.1±1.9	60.2±2.0	22.5±1.4	120±3
Apr18	65	62.1±2.7	60.2±2.0	59.5±1.9	63.3±2.3	21.8±2.2	117±4
Apr19	66	58.9±2.8	58.5±2.0	59.8±2.1	62.2±2.2	23.6±2.3	116±4
May 1	78	53.4±2.9	56.9±2.3	59.1±2.1	57.8±2.1	17.6±4.1	109±4
May 5	82	56.9±2.8	58.9±2.1	60.9±2.1	58.4±2.2	25.4±3.1	105±4
May 6	83	64.4±3.6	56.0±1.9	60.1±2.0	58.2±2.0	17.5±2.0	114±3
May 7	84	61.5±2.8	57.4±2.0	60.5±1.9	60.5±2.1	22.5±2.4	120±4
May 9	86	60.8±2.1	59.9±1.9	60.1±1.9	62.1±2.1	24.0±1.2	116±3
May14	91	62.1±2.6	59.1±2.1	58.0±2.0	64.6±2.4	22.4±3.1	100±4
May17	94	62.6±2.5	61.5±2.0	62.7±2.1	66.3±2.3	21.7±2.0	104±3
May19	96	63.4±3.5	58.6±2.1	59.6±2.0	58.7±2.6	21.3±3.6	114±5
May23	100	66.7±2.6	65.9±2.1	65.2±2.0	67.1±2.1	22.9±2.7	111±3
May26	103	63.4±2.6	62.3±2.1	63.2±2.0	65.7±2.3	25.0±1.7	108±4
May27	104	65.3±2.9	61.2±2.1	62.2±2.1	62.2±2.0	24.6±2.8	121±3
Jun 2	110	69.6±3.7	63.6±2.4	69.7±2.6	65.6±2.6	29.0±5.4	129±5
Jun 3	111	87.6±4.4	71.2±2.6	67.7±2.7	73.7±3.1	21.3±4.0	122±5
Jun 4	112	64.8±2.5	60.7±2.0	61.9±2.0	60.2±2.1	28.8±2.1	128±4
Jun 6*	114	69.7±2.4	62.6±2.0	62.5±1.9	63.8±2.1	31.9±1.6	115±3
Jun 8*	116	64.5±2.5	62.9±2.0	65.8±2.1	67.9±2.2	21.7±2.9	117±3
Jun10	118	74.2±2.9	63.6±2.1	64.9±2.1	65.4±2.4	22.7±2.4	126±4
Jun13	121	67.3±3.2	65.3±2.1	65.9±2.1	67.0±2.2	28.3±1.8	124±4
Jun16	124	75.6±3.2	66.6±2.3	64.0±2.1	67.9±2.5	24.8±3.0	127±4
Jun19	127	70.0±3.0	62.2±2.1	64.4±2.3	67.9±2.7	27.1±1.4	124±5
Jun26	134	70.9±3.3	67.4±2.2	68.5±2.3	67.9±2.3	33.5±2.6	131±4
Jul 3	141	79.4±2.8	71.3±2.3	69.1±2.2	70.1±2.2	29.6±1.4	131±4
Jul 7	145	66.9±2.4	64.5±2.0	65.7±2.1	66.9±2.3	30.8±2.3	126±4
Jul11	149	73.7±3.1	65.8±2.1	66.7±2.2	66.1±2.2	30.7±2.9	136±4
Jul12	150	74.5±2.9	66.7±2.1	65.2±2.1	67.3±2.3	28.8±2.2	132±4
Jul17	155	75.3±2.7	69.3±2.2	69.1±2.3	69.4±2.2	30.9±2.0	125±4
Jul18*	156	76.1±3.0	69.3±2.3	68.7±2.2	72.0±2.3	30.6±3.6	127±4

NOTES.—Day 1 = J.D. 2447205.

Continuum, in the specified bands, in units of 10^{-16} ergs s^{-1} $Å^{-1}$ cm^{-2}; Hα and Hβ in units of 10^{-14} ergs s^{-1} cm^{-2}.

Asterisks (*) denote photometric nights on which standard stars were observed.

As an alternative method of measurement, we determined by eye the continuum level at the same spectral bands. Although not as objective, this method has the advantage of disregarding spurious features in the spectrum, such as bad pixels, improperly subtracted sky lines, and residual cosmic-ray events. The uncertainty was found by estimating the upper and lower bounds where the continuum could reasonably be set. The results of these measurements were the same as those using the previous method, to within the uncertainties. In what follows, we quote the results of the first, automated, measurements.

To estimate the systematic errors in our observing procedure, we repeatedly observed and measured a Seyfert 2 galaxy, Mrk 3, in exactly the same fashion. This galaxy has the potential for producing systematic aperture effects; an extended narrow-line region and a very strong and extended stellar continuum. On the other hand, Seyfert 2 galaxies do not vary on short time scales, so the spread in the results can give an estimate of the accuracy of the method. An additional error estimate comes from the results for another Seyfert 1 galaxy in our sample, NGC 3516, which did not vary during the monitoring period.

We observed Mrk 3 on 12 nights in December through February, and again after a year, in 1988 December. We used as a comparison the 10th magnitude star 3′ south and 2′ west of the galaxy. The continuum measurements of *all* these spectra fall within a range of $\pm 6\%$ of the mean in the various bands, defined as for Mrk 279. The standard deviation is about $\pm 3\%$. The Hα intensity distribution in all these spectra has a 1 σ of 3%.

NGC 3516 was observed in 1987 December through 1988 July. We obtained acceptable spectra, as defined above, on 53 nights out of 218 days. The 11th magnitude star 4′ west of the galaxy was used as a comparison. The observations, reduction, and measurements were carried out exactly as for Mrk 279,

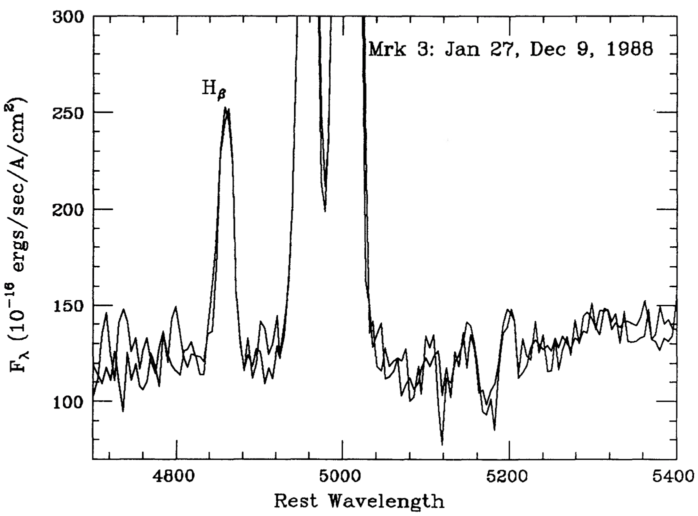

FIG. 1a

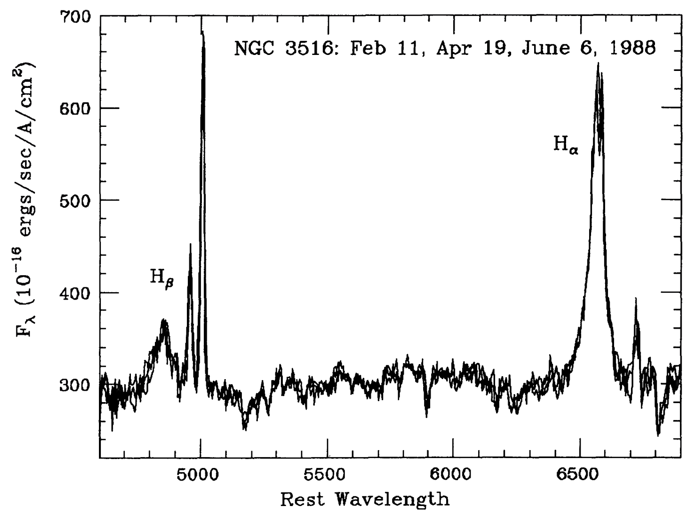

FIG. 1b

FIG. 1.—Two spectra of Mrk 3 at different epochs (nonphotometric nights). (*b*) Three superposed spectra of NGC 3516 at different epochs. Only June 6 was a photometric night.

except that a scaled down and properly redshifted M31 spectrum was subtracted from each NGC 3516 spectrum prior to measurement. This was done to eliminate from the spectrum the strong stellar absorption lines present in the continuum of NGC 3516 and thus define better the nonstellar continuum. Since this galaxy is 4 times nearer than Mrk 279 and has a strong stellar continuum, it is also potentially more susceptible to systematic errors. Furthermore, it is relatively bright, so that the errors due to counting statistics become very small, while any systematic errors in our method should become dominant.

Figures 1*a* and 1*b* show several superposed spectra of Mrk 3 and of NGC 3516, respectively. The diagrams indicate that the method is potentially very accurate for broad as well as for narrow lines, and for the continuum level. Figure 2 shows the total continuum flux density of NGC 3516 in one of the four continuum bands, defined as for Mrk 279, over the whole period. It is apparent that there is negligible variability. All the points fall in the range of $\pm 5\%$ of the mean in the various

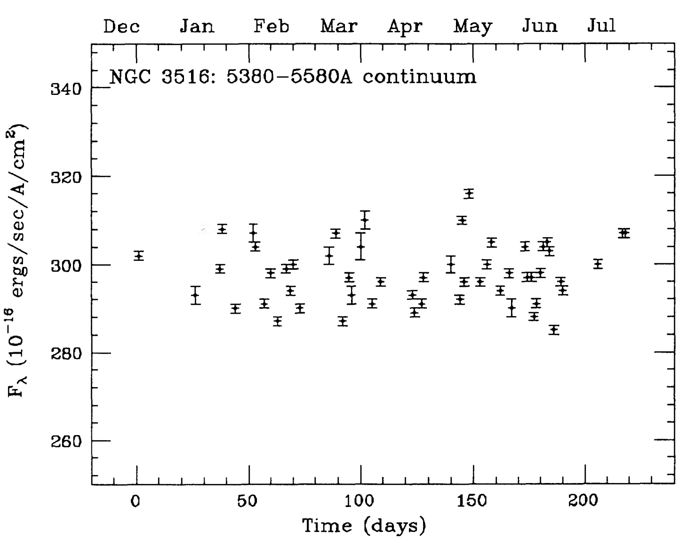

FIG. 2.—The 5380–5580 Å continuum light curve of NGC 3516 between 1987 December and 1988 July. Error bars denote the 1 σ statistical error.

bands. A χ^2 minimization shows that the points have a spread that is well fitted by a normal distribution, as is expected of a random error, with a 1 σ of $\sim 3\%$ about the mean in the various bands. This is similar, and probably due, to the expected error due to our lack of flat-field correction and the slight ($\sim 1\%$) error introduced when smoothing the comparison star spectrum. It is also possible that this spread in the points results from a real change in the nucleus, as NGC 3516 is a known variable Seyfert. The Hβ flux of NGC 3516 also appears constant to $\pm 8\%$ (the larger error here results from a propagation of the error in setting the underlying continuum). Hα displays an erratic variation of $\pm 5\%$ which is probably due to the same measuring error, but a general trend of monotonic decrease by $\sim 10\%$ is also present.

From these two estimates, we adopt a value of $\pm 3\%$ for the 1 σ error in the calibration of the continuum of Mrk 279. To this we add the statistical error as derived from the noise measured in the continuum of each spectrum. The error in the lines is calculated by combining this 3% calibration error, the propagation of the error in setting the continuum, and the statistical error in the flux due to noise. The typical error is $\pm 4\%$ for Hα and the continuum measurements. The relatively low signal in Hβ compounded with the uncertainty in the determination of its underlying continuum cause a large uncertainty (typically 10%) in this line.

Table 1 gives our measurements and their errors for Mrk 279. Figure 3 shows two superposed spectra of Mrk 279, and Figure 4 shows several of the line and continuum light curves.

IV. RESULTS AND DISCUSSION

a) Line and Continuum Light Curves

It appears from the light curves that the continuum of Mrk 279 did not vary much during the first 80, or so, days of monitoring (Maoz 1989), although some changes may have occurred during three gaps in the sampling. Then, in May, a slow brightening began and continued until mid-July, when the observations ended. At that time the continuum was $\sim 30\%$ brighter in the blue part of the spectrum, and $\sim 15\%$ in the red, than at the start. Possibly superposed on this slow

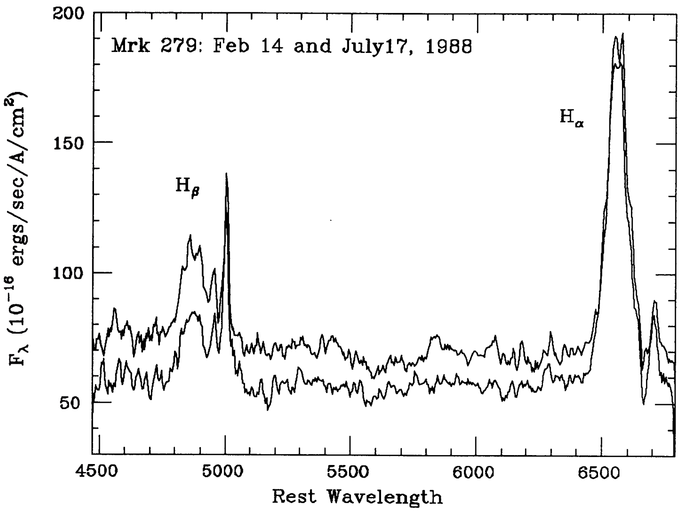

FIG. 3.—Two superposed spectra of Mrk 279 at different epochs

variation are some more rapid variations whose reality cannot be determined, since their amplitude is comparable to the error.

Hβ followed a similar trend, brightening gradually in May and then leveling off in June at a strength $\sim$50% greater than at the start. The relatively large error in this line makes the details of its light curve uncertain.

Hα underwent fluctuations of order 10% in strength on various time scales from the start, and then also brightened during May, staying at a more or less constant level in June–July, 20% above its strength at the start. The variation of the Balmer decrement with continuum luminosity is well known and has been observed before in Seyfert galaxies (e.g., Wamsteker *et al.* 1989). Some of the fluctuations in the line strength, if real, are surprisingly fast; on three consecutive nights (days 82, 83, 84) Hα increased in strength by 15%.

In view of these results, an additional source of error to be considered is that the variability is not of Mrk 279 but of the comparison star used. In such case one would expect to see the same degree of variation in an emission line and a continuum band adjacent to it. The results seem to rule out this possibility. In addition, five spectra of the comparison star taken on photometric nights on which standard stars were observed, and calibrated independently, are constant to within 5% of each other. These observations, on days 30, 61, 114, 116, and 156, were made both before and after the apparent brightening of Mrk 279.

As an additional check for this or other systematic effects in our results, we measured the [O III]λ5007 line, which is generally accepted to be constant on these time scales. Such a measurement is not straightforward due to the low signal of this line in our spectra and the uncertainty in setting the underlying continuum, composed of the red wing of Hβ and blended Fe II emission, both of which may be variable. The [O III]λ5007 fluxes in our spectra have a standard deviation of 8% about the mean (1.55×10^{-13} ergs s^{-1} cm^{-2}). To increase S/N we formed the average of the 17 "low state" spectra (February 14–May 9) and of the 16 "high state" spectra (June 2–July 18). The [O III]λ5007 flux in the two average spectra is the same to within 1%–8% (depending on the setting of the continuum) and is always *lower* in the "high state" spectrum, as opposed to what would be expected from a systematic calibration error.

b) Cross-Correlation Analysis

To determine the size of the BLR in Mrk 279 from the lag in the emission line response to changes in the continuum, we cross-correlated the various light curves we obtained. Figure 5 shows the cross-correlation functions (CCF) of Hα and Hβ, respectively, with the averaged (over the three bands indicated) continuum. The line and continuum light curves were linearly interpolated in order to calculate the CCF. We attempted using other methods of interpolation and obtained the same CCF, as is expected at our high sampling rate.

The CCF of Hα versus the continuum has a very high, flat-topped peak at a lag of 0–20 days. A parabolic fit to the upper third of the CCF has a maximum of 0.82 at a lag of +12 days with a formal error of ± 1 day. The CCF reaches half its maximum value at lags of -25 and $+50$. The CCF of Hβ versus the continuum has a similar, although somewhat noisier, structure. A parabolic fit to its upper third has a maximum of 0.75 at a lag of 10 days. The CCFs of the emission lines versus the individual continuum bands are very similar, except for those using the reddest (6325–6425 Å) band, where the lower amplitude of variation results in a lower peaked CCF. This band is also possibly contaminated by some far blue wing Hα emission.

Our results thus indicate a very small BLR for Mrk 279, considering its brightness, as discussed in § IV*c*, below.

To determine the significance of these results and estimate the uncertainty in the BLR size they imply, we performed Monte Carlo simulations as described by Maoz and Netzer (1989). The Hα and Hβ results are similar enough (in terms of the lag and the ratio of the variation amplitude to the measuring error) to concentrate the discussion on one of them, Hα. A model light curve for the continuum of Mrk 279 was created by assuming the flux to have been constant during the first 80 days, then to have increased linearly for 40 days, and finally to have been constant again, at the high level, to the end of the observing period. Such a model light curve fits the data well (see Fig. 4*a*), although the fit is not unique. The response of a variety of BLR geometries to such an ionizing continuum was calculated assuming that the lines respond linearly to continuum changes, each geometry giving a model emission-line light curve. The model line and continuum light curves were then sampled at random on 39 epochs, and a random "measurement error," typical of a measuring error for Mrk 279, was added. The resulting light curves, each having the same number of points as the real data, were cross-correlated and the peak of the CCF found through a parabolic fit. The random sampling process was repeated 500 times to obtain the cross correlation peak distribution (hereafter CCPD; see Maoz and Netzer 1989) and determine the probability of obtaining a certain cross-correlation result, given an assumed BLR geometry.

Based on the assumptions above, we find from the simulations that the results rule out at the 95% significance level, or better, the following BLR geometries (chosen to typify some common models) for Mrk 279; (1) any thin shell or ring with a radius of 21 lt-days or larger, or thick shell with inner radius 21 lt-days or larger; (2) any face-on ring of radius 18 lt-days or larger, or rings with axis inclined by less than 40° to the line of sight and of radius 20 lt-days or larger; (3) any thick shell of inner radius 10 lt-days and outer radius greater than 50 lt-days; and (4) any thin shell or ring of radius smaller than 6 lt-days (this is comparable to our sampling rate and should therefore be regarded with caution.)

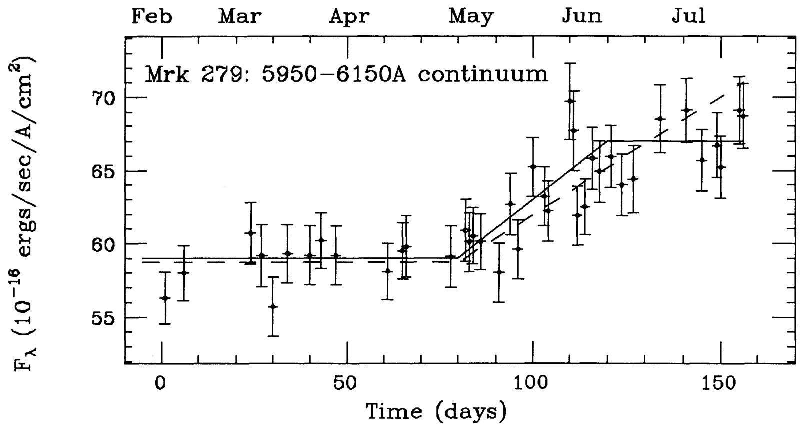

FIG. 4*a*

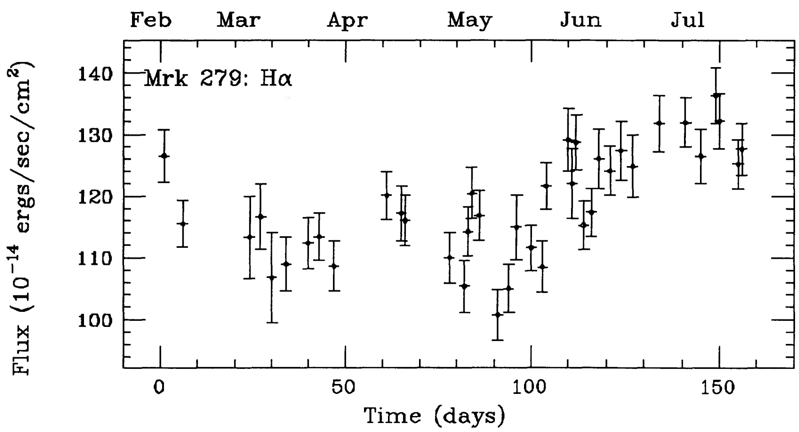

FIG. 4*b*

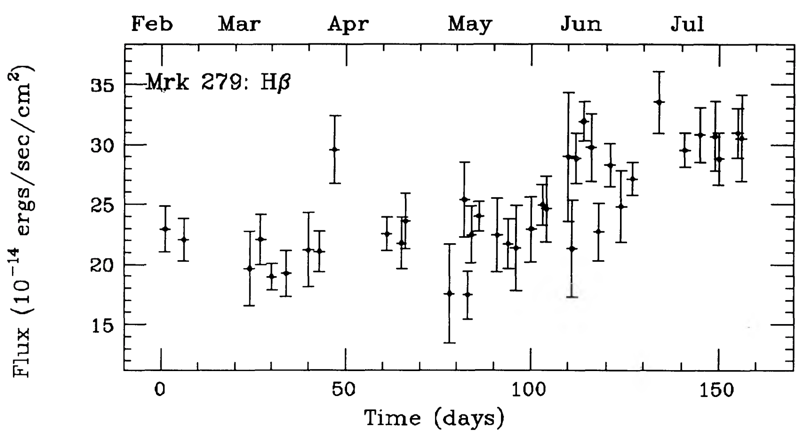

FIG. 4*c*

FIG. 4.—Line and continuum light curves of Mrk 279. (*a*) The 5950–6150 Å continuum. Error bars denote the 1 σ uncertainty, as explained in text. Also shown are two possible model continuum light curves, as discussed in § IV*b*. (*b*) Hα. (*c*) Hβ.

Clearly, the observed line variation could be the response of the BLR to a much earlier continuum brightening event. Models of radii much larger than discussed above cannot be confidently excluded unless a time base several times the light-travel time across the model is available. Our data, being of only one season's length does not permit this. The high correlation at a small time lag does, however, suggest that the emission-line brightening is in response to the continuum brightening observed in 1988, and not to some previous variation.

We also note that, due to the peculiar form of the variability observed, the conclusions are sensitive to the choice of model light-curves; in particular, if the continuum were in reality rising monotonically after beginning to brighten and not leveling off toward the end, any spherical geometry would respond immediately with an emission-line light curve that

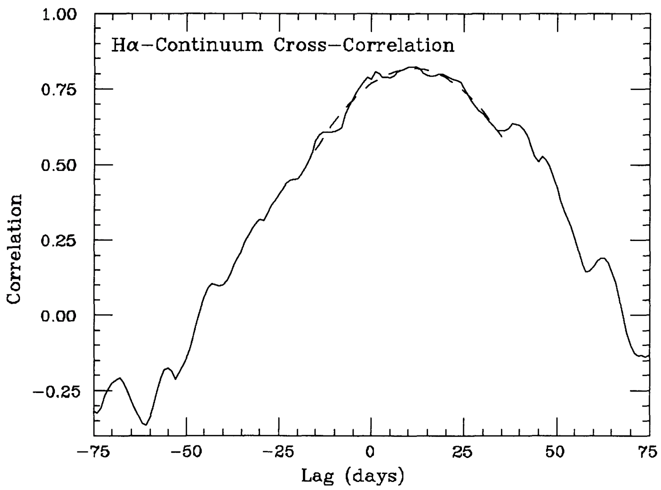

FIG. 5*a*

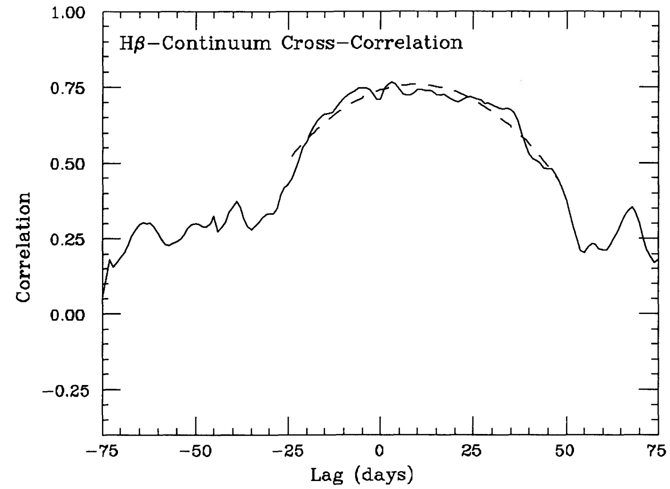

FIG. 5*b*

FIG. 5.—Cross-correlation functions: (*a*) The cross-correlation function of Hα vs. the average continuum. The continuum light curve was averaged over the 4630–4730 Å, 5380–5580 Å, and 5950–6150 Å bands. Also shown (*dashed curve*) is a parabola fit to the upper third of the CCF. (*b*) Hβ vs. the average continuum.

also rises monotonically. (Such a monotonically rising continuum is shown in Fig. 4*a*.) In such a case the cross-correlation technique fails, and the peak of the CCF does not yield the true BLR dimensions. To check if this is the case, one must use additional information, such as the shape of the emission-line light curve. Our observed Hα and Hβ light-curves suggest a leveling-off toward the end of the observing period, such as would be expected from the response to the first model continuum light curve we have chosen, and not the second (monotonically rising) one. None of various other model continuum light curves we have experimented with yield an emission-line light curve with such a feature. In addition, the CCF resulting from such monotonically rising light curves is usually broader, by a factor of 2 or more, than the observed CCFs of the lines and the continuum.

As explained in Maoz and Netzer (1989), the Monte Carlo simulations can also be used to estimate the equivalent of the 1 σ uncertainty (i.e., the 68% probability range) in our 12 day lag result for Hα. Our simulations show that if one assumes: (*a*) a thin shell or ring-shaped BLR of radius 12 lt-days (*b*) the model continuum light curve described above, and (*c*) the error in the lines is of 0.2 the amplitude of the variation (as it is for both Hα and Hβ); then there is a 68% probability of obtaining a cross-correlation peak at a lag of 12 ± 3 days. Thus, the Hβ result is also consistent with a 12 lt-days BLR. If one assumes a BLR based on the Hβ result (i.e., 10 lt-days) then the 68% range is 10 ± 3. The fact that models which can be ruled out at the 95% significance level are three "sigmas" away is the result of the shape of the CCPD, which is non-Gaussian and asymmetric toward shorter lags for the specific type of continuum light curve dealt with here.

The 12 ± 3 result is independent of the assumed type of BLR geometry, since, with such long continuum variability time scales and short emission-line response times, both flat and spherical geometries respond coherently and indistinguishably to changes in the continuum. Choosing a less "well behaved" model continuum light curve also has little effect; e.g., adding to the model continuum a 1/f type noise, of spectral components with periods shorter than those sampled by us (i.e., < 8 days) and amplitude which is still consistent with the data, results in a CCPD of 12 ± 4 days. Choosing a model continuum with more structure on longer time scales yields a narrower CCPD, as this structure is reflected in the model emission line light curve, thus enhancing the correlation. Since, as described above, Hα has a light curve with clearer structure, giving a slightly higher and more sharply peaked CCF than for Hβ, we adopt the Hα result.

Our data therefore indicate a BLR-size of 12 ± 3 lt-days for Mrk 279.

c) Comparison with Photoionization Theory

The UV spectrum of Mrk 279 is similar to that of other Seyfert 1 galaxies. We can therefore estimate the size of its BLR within the framework of the "standard" photoionization model (e.g., Davidson and Netzer 1979; Kwan and Krolik 1981; Mushotzky and Ferland 1984). Using $F\nu$ (1350 Å) from Chapman, Geller and Huchra (1985), we estimate:

$$R_{\rm BLR} \sim 200(H_0/50)^{-1}(U/10^{-2})^{-0.5}(N_{10})^{0.5} \text{ lt-days} ,$$

where H_0 is the Hubble constant in km s^{-1} Mpc^{-1}, U is the dimensionless ionization parameter, and N_{10} is the electron density in units of 10^{10} cm^{-3}. Acceptable values for these parameters of $U \sim 10^{-2}$, $N_{10} \sim 1$, and $H_0 = 50$ give $R \sim 200$ lt-days. Our result, an order of magnitude smaller, conflicts with photoionization models for a spherical BLR with such values of U and N. This discrepancy was first pointed out in general by Peterson *et al.* (1985) and Gaskell and Sparke (1986). A flat BLR geometry could be accommodated with somewhat larger U and smaller dimensions (Netzer 1987), but probably not as small as those found here. All this is in line with the convergence of BLR–size results toward ~ 30 lt-days for Akn 120 (Peterson and Gaskell 1989; Alloin *et al.* 1988), also an order of magnitude below the spherical model prediction for that galaxy. We should stress, however, that our sampling rate of Mrk 279 is far better than that obtained so far for Akn 120.

Due mainly to the small amplitude of variation (30%) we encountered, its long time scale, and the fast response, our data cannot yet establish the type of BLR geometry present in Mrk 279. Nevertheless, some features of the light curve are suggestive; the sharp 15% increase in Hα within two days could occur if the line-emitting gas was in a highly asymmetric concentration (in which case the lag between lines and continuum gives only twice the lower limit to the distance between the continuum source and the BLR). Alternatively, such a feature could still occur in the light curve if the BLR had the geometry of a nearly face-on ring.

V. CONCLUSIONS

We have presented the first results of a spectrophotometric monitoring program carried out at the Wise Observatory during 1987–1988, aimed at mapping the BLR of AGNs. A novel observing method, based on the simultaneous observation of a comparison star in a long-slit spectroscopy mode, enabled us to obtain high accuracy and absolute flux calibration even during periods of full moon and bad weather. In addition, we achieved a temporal sampling rate unprecedented in studies of this kind. In the results of the program presented here concerning Mrk 279, we are thus able to resolve a relatively small variation that occurred during the period of observation. Cross-correlation of the light curves of Hα and Hβ with the continuum gives results consistent with a BLR of radius 12 ± 3 light days. A symmetric BLR larger than 21 light days can be significantly ruled out. This is in clear contradiction with the "standard model" prediction of BLR size.

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