OPTICAL SPECTROSCOPY AND NARROW-BAND IMAGES OF THE VARIABLE SEYFERT 1 GALAXY NGC 3783[1]

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ABSTRACT

We present narrow-band images centered on [O III] $\lambda5007$, Hα, and adjacent continua of the Seyfert 1 galaxy NGC 3783. The continuum images evidence that the bar emission is mainly due to old stars. The [O III] $\lambda5007$ image shows that the high-excitation gas is very concentrated while the Hα emission is more extended and elongated perpendicularly to the direction of the bar.

Ten new optical spectra, obtained between 1987 and 1990, are used to study the variability of the continuum and emission lines in this galaxy. The contribution of the bulge stellar population to the nuclear spectrum is determined for each epoch and subtracted. The remaining optical continuum is then decomposed in two variable components, and after these components have been subtracted, the resultant spectra, constituted by pure line emission, are analyzed. A multiple Gaussian components model is found in order to describe the different emission lines on the various spectra. With the results of this decomposition the structure and physical conditions of the emission-line regions are determined. The variations in the continuum and emission-line fluxes are then analyzed, and the relations between them are pointed out.

Subject headings: galaxies: individual (NGC 3783) — galaxies: Seyfert — galaxies: stellar content

1. INTRODUCTION

NGC 3783 is a southern Seyfert 1 galaxy with very strong emission lines, and it was the subject of several investigations: optical spectrophotometry has been carried out by Martin (1974), Osmer, Smith, & Weedman (1974), Cooke et al. (1976), and Penston et al. (1977); mid-infrared photometry was made by Glass et al. (1982), and *IUE* spectra were analyzed by Barr, Willis, & Wilson (1983) and Wamsteker & Barr (1985). It is an X-ray source (Cooke et al. 1976), and its X-ray spectrum is known to be variable (Branduardi-Raymont et al. 1985). Analysis of the emission-line profiles has been performed by Pelat, Alloin, & Fosbury (1981), and by Evans (1988). Variability of the nuclear continuum light in the optical and infrared has been reported by Penfold (1979), Glass (1979), de Ruiter & Lub (1986), and Hamuy & Maza (1987). Strong variations of the broad component of the Balmer and He lines were observed, not only in flux (Atwood, Baldwin, & Carswell 1982; Ward & Morris 1984; Morris & Ward 1988; Stirpe, de Bruyn, & van Groningen 1988; Evans 1989), but also in shape (Menzies & Feast 1983).

In this paper we present narrow-band imagery (Hα and [O III] $\lambda5007$) and 10 new optical spectra of this galaxy, analyzing the gas morphology and extension, the bulge stellar population contribution to the nuclear spectra, and the continuum

and emission-line shapes and variability. A value of $H_0 = 50$ km s^{-1} Mpc^{-1} is assumed throughout this work.

2. THE OBSERVATIONS

The data analyzed here consist of 10 optical spectra obtained at three observatories: the Cerro Tololo Interamerican Observatory (CTIO, Chile), the Laboratório Nacional de Astrofísica (LNA, Brazil), and the Complejo Astronómico del Leoncito (CASLEO, Argentina), including different spectral ranges between 3700 and 8000 Å with resolutions from 5 to 14 Å, and four CCD images centered on (redshifted) Hα $\lambda6563$ and [O III] $\lambda5007$ lines, and adjacent continua.

2.1. The CCD Images

The images were obtained with the CTIO 91 cm telescope plus CCD Ti2 on 1990 March 11–13. The integration times and filter specifications are listed in Table 1. The image scale is $0\overset{''}{.}494$ pixel^{-1}. The reduction of the images follows standard procedures (IRAF packages). The flux calibration was made using images of standard stars from Stone & Baldwin (1983). Once flux calibrated each continuum image was subtracted from its respective line + continuum one, to produce the pure Hα and pure [O III] emission images (hereafter pHα and p[O III], respectively).

2.2. The Optical Spectra

NGC 3783 was observed in 10 epochs during the period 1987 March to 1990 June. The log of observations is presented in Table 2. The columns list by order the following:

The run number (as each observation will be referred to hereafter);

TABLE 1

OBSERVING LOG: CCD IMAGES

Image (1)	Date (2)	T_{exp} (s) (3)	λ_0 (Å) (4)	FWHM (Å) (5)	Peak (6)
Hα	1990 Mar 11	900	6606	75	242
Hα Continuum	1990 Mar 11	1200	6477	75	40
[O III]	1990 Mar 13	900	5057	15	42
[O III] Continuum	1990 Mar 13	900	4740	190	22

NOTES.—Col. (3): Total integration time, in seconds; col. (4): filter central wavelengths; col. (5): filter widths; col. (6): innermost isophotes values, in units of 10^{-15} ergs cm^{-2} s^{-1}.

The observation date, with the correspondent JD conversion;

The telescope/detector used;

The slit dimensions (the table gives the slit width [N–S] × length [E–W] dimensions. When only one figure is given, it corresponds to the slit width, and the spectra are integrated over the total extension of the galaxy);

The wavelength coverage/final resolution of each spectrum.

All the spectra were reduced following standard spectrophotometric techniques and flux calibrated using standard stars from the lists of Oke & Gunn (1983), Stone & Baldwin (1983), and Taylor (1984).

The nuclear spectra were corrected from reddening using the curves of Seaton (1979), and adopting a color excess $E(B-V) = 0.09$, due to the Galactic extinction only.

The redshift of each spectrum was obtained by averaging the values separately calculated from the observed main forbidden emission lines and narrow components of Hα and Hβ, and the individual data were corrected by this mean. The value obtained for the systemic velocity of NGC 3783 from the whole set of observations is $v = 2930$ km s^{-1}, which gives a distance of 58.6 Mpc for the galaxy and a linear scale of 285 pc arcsec^{-1}.

During the 1987 CTIO run, we have also obtained a spectrum of a region 8″ north of the nucleus. Another off-nuclear spectrum was extracted from the 2D-FRUTTI original frame of the 1988 observation, being composed by the sum of two 25 arcsec^2 regions centered 5″ east and west of the nucleus. These spectra were reduced the same way as the nuclear ones, but were also corrected by an additional color excess (internal to the galaxy) of $E(B-V) = 0.14$ (Forte et al. 1987). They have

FIG. 1.—The Hα + continuum image, with the structures discussed in the text. Contours from $F_\lambda = 0.2$–2.0.

been already analyzed by Winge, Storchi-Bergmann, & Pastoriza (1990), and we will briefly summarize these previous results in § 4.2.1, where we discuss the stellar population of NGC 3783 and its contribution to the nuclear light.

The spectra of runs 4 and 5 are constituted by the average of three and two observations, respectively, obtained on consecutive nights on 1989 May 9–11 and June 27–28. These spectra have been analyzed to search for variability on time series scales of 1 or 2 days, but we found no evidence of such short-time variations.

3. IMAGES AND MORPHOLOGY OF THE GAS EMISSION

Figures 1–3 show the CCD images, the lowest isophotal level of each image being placed 1 σ above the residual background left by the sky subtraction. The contours on these figures are given in flux units of 10^{-15} ergs cm^{-2} s^{-1}, and as we are mainly interested in the disk and near-nucleus features, only the isophotal contours up to the $F_\lambda = 2.2 \times 10^{-15}$ ergs cm^{-2} s^{-1} level are shown. The values of the peak isophotes are given in Table 1.

TABLE 2

OBSERVING LOG: OPTICAL SPECTRA

Run (1)	Date (2)	JD (2,441,000+) (3)	Equipment (4)	Slit (5)	Interval/Resolution (6)
1	1987 Mar 2	5857	1.0/2DF	5 × 8	3700–7100/5
2	1988 May 10	6292	1.0/2DF	5 × 5	3600–6900/5
3	1988 Jun 8	6321	1.6/OMA	6	4600–8900/12
4	1989 May 8	6655	1.6/OMA	3	4450–8100/14
5	1989 May 10	6657	2.15/Rt	3	4400–6900/7
6	1989 Jun 28	6706	2.15/Rt	3	4650–7100/7
7	1989 Jul 15	6723	1.6OMA	3	4500–7100/14
8	1990 Mar 3	6954	1.0/2DF	2 × 8	3600–7050/5
9	1990 Mar 27	6978	2.15/Rt	3	4250–7100/7
10	1990 Jun 25	7068	2.15/Rt	3	4650–7600/7

NOTES.—Column (4): 1.0/2DF = CTIO 1.0 m + 2D FRUTTI; 1.6/OMA = LNA 1.6 m + OMAIII; 2.15/Rt = CASLEO 2.15 m + Reticon; col. (5): slit dimensions in arcseconds; col. (6): interval and resolution in Å.
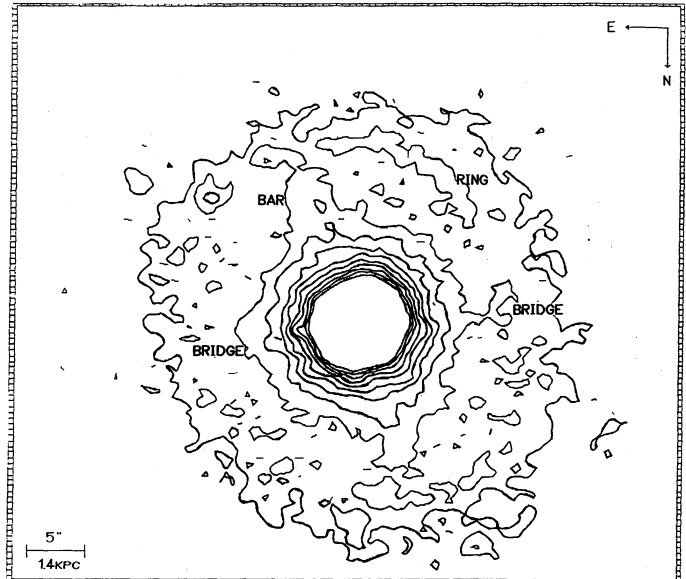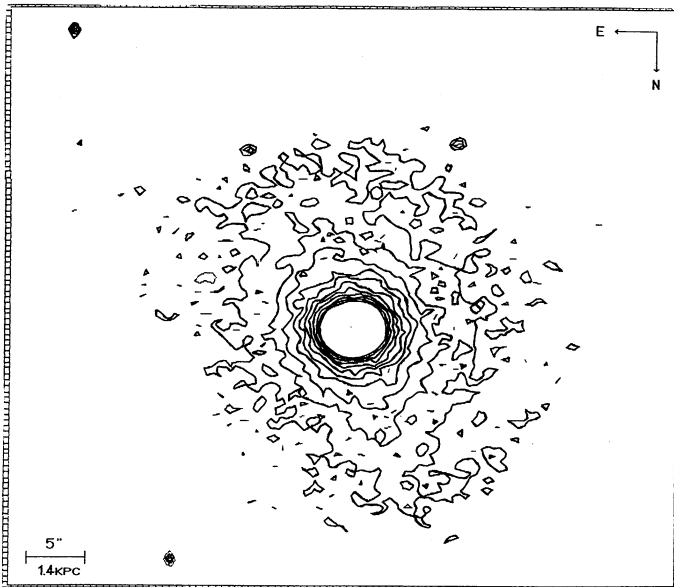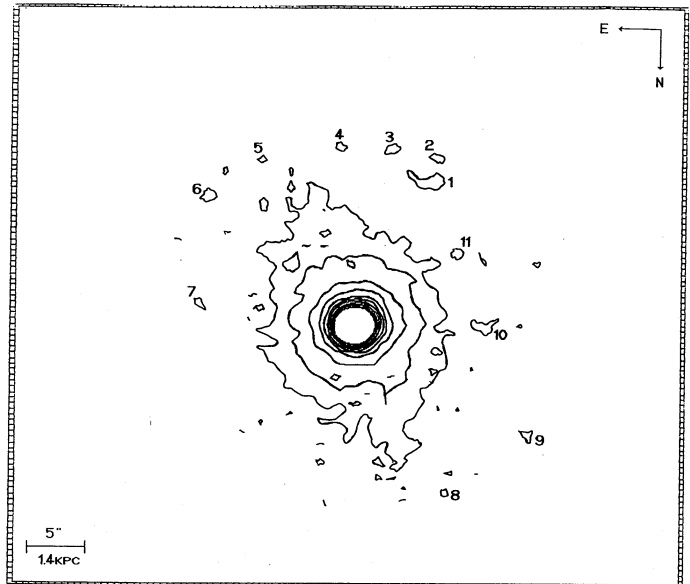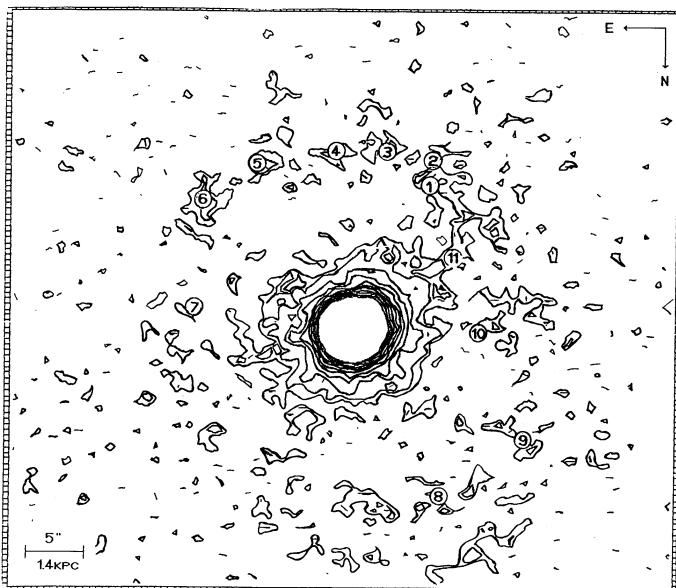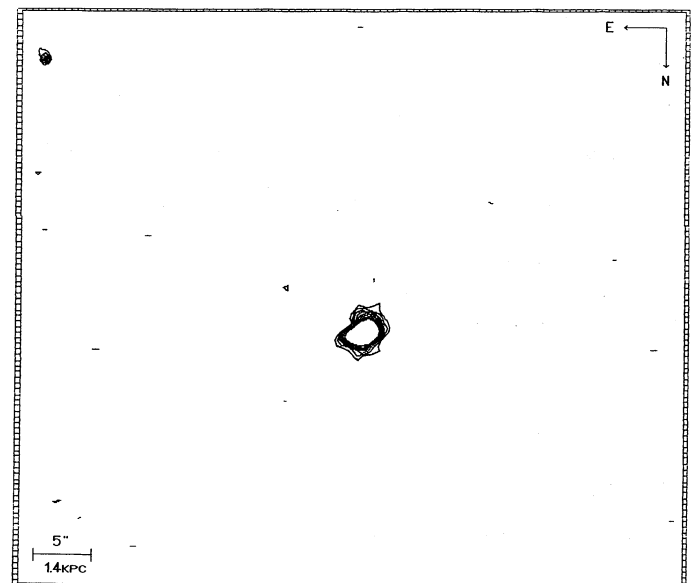
FIG. 2a

FIG. 2b

FIG. 2c

FIG. 2d

FIG. 2.—(a) Red continuum (contours at $F_\lambda = 0.2, 0.4$, etc.); (b) blue continuum ($F_\lambda = 0.1, 0.2, 0.4$, etc.); (c) pure Hα ($F_\lambda = 0.1, 0.2, 0.4$, etc.); and (d) pure [O III] ($F_\lambda = 0.2, 0.4$, etc.) images.

The main structures of interest are indicated on Figure 1, over the Hα + continuum image. Clearly visible are the bar (at P.A. = 163°5; Forte et al. 1987, hereafter F87), parts of the inner ring, and two structures oriented perpendicularly to the bar, already detected by F87 and that they called "the bridges." The western bridge is more evident, joining the central isophotes and the ring.

As our blue (4740 Å) continuum image includes the contribution from the He II λ4686 line in the filter bandpass, we have estimated it applying the filter response curve over the run 8 spectrum (that is, approximately contemporaneous with the images) and obtained that it is of about 7% for the inner

2″ × 8″ region. So we can expect a small underestimation of the p[O III] flux, but the shape of the image contours will remain essentially unchanged, even if the He II λ4686 and [O III] emission gas distributions are different.

In Figure 2, corresponding to the continuum and pure-line images, we can observe that the central contours (up to a 5″ radius) are nearly circular on all the images, except p[O III], where the isophotes are asymmetric, being elongated in the direction of the bridges, as can be more clearly seen in the enlargement of the central 10″ × 10″ (Fig. 3). The regular contours for a field star (shown as an insert on Fig. 3) confirm the reality of this asymmetry. The external contours are progres-
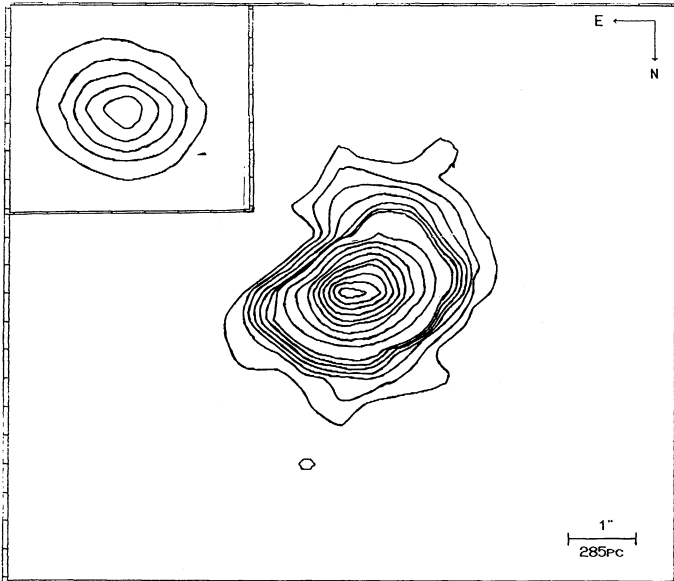
FIG. 3.—Enlargement of the inner 10″ × 10″ of Fig. 2d

sively more elongated, and oriented following the direction of the bar on the continuum images, but perpendicularly to it on the pHα one.

A very interesting and evident characteristic (see Figs. 1 and 2c, Hα + continuum and pHα images, respectively) is the absence of Hα emission along the bar, while the emission along the bridges (mainly at P.A. ≃ 230°, the western bridge) is easily seen. It can also be noted in the inner ring and part of the northern spiral arm.

From the superposition of the pHα and the blue (4740 Å) continuum images, we notice that the knots that appear on the continuum image (numbered 1–11) are coincident with the brightest regions of Hα emission on the inner ring.

Considering the features described above, we can conclude that the high-excitation gas (responsible for the [O III] emission) is highly concentrated and slightly asymmetrically distributed, extending up to 400 pc from the nucleus on our image. The Hα emission is also asymmetric, being elongated perpendicularly to the bar direction, and extends to more than 2 kpc. The presence of the bridges in the direction of the elongation points toward the existence of a liaison between the gas of the nuclear region and that of the ring. It is also important to point out that the absence of gas emission along the bar, that is observed only on the continuum images. The fact that the bar is brighter in the red (6477 Å) than in the blue (4740 Å) continuum indicates that old stars are responsible for the majority of the flux from this structure. Since the blue continuum represents the emission from the younger stellar population, and recalling that the outer "knots" in Figure 2b are coincident with the brightest parts of pure Hα emission of the ring, we can conclude that the gas in the inner ring is ionized by hot stars.

Finally, since the emission that characterizes the bridges is much stronger on the pHα image than on the Hα continuum one, we can attribute such emission to gas ionized by a power-law spectra (Winge et al. 1990), instead of to electron scattering of the central source continuum, as suggested by F87.

4. SPECTRA

4.1. Normalization

It became a usual practice in optical variability studies to use the strongest forbidden line fluxes (usually [O III] λ4959 and/or λ5007) to normalize different spectra to the same flux scale.

This kind of "internal calibration" could reach an accuracy on the line fluxes better than 5% (Stirpe et al. 1988; Peterson et al. 1991), but requires the whole narrow-line region (NLR) of the observed AGN to be contained inside the spectrograph slit during all the integration time of each observation.

As discussed in § 3, the [O III] λ5007 emission in NGC 3783 is very concentrated. From a north-south profile extracted from our p[O III] image, we have found that about 99% of the [O III] λ5007 emission in this image comes from the central 5″ × 5″ (1.4 × 1.4 kpc) region. The smallest slit width used in our set of spectra (2″ × 8″) still contains more than 87% of this line emission. A similar analysis performed on a profile extracted from the pHα image yields that a 5″ × 5″ slit corresponds to 95% of the Hα emission. Assuming that the [O III] line flux is constant over the entire set of observations (Peterson 1988), we have measured the [O III] λ4959 flux in all the spectra and normalized the data to the flux of this line in the 1988 May 10 (run 2) spectrum, $F_{[O\ III]\ \lambda4959} = 105 \times 10^{-15}$ ergs cm^{-2} s^{-1}.

Since the [O III] λ4959 line is located just over the red wing of Hβ, the reference spectrum is selected as the one where this contamination was smaller, and we have used the [O III] λ4959 rather than the stronger [O III] λ5007 due to the fact that the latter is saturated on the run 3 (and possibly on the run 7) spectrum.

As already pointed out in § 1, NGC 3783 is a strongly variable Seyfert 1 galaxy. This behavior can also be seen in our data when comparing the normalized spectra: Figure 4 shows the run 2 and 8 spectra (that can be interpreted as states of "low" and "high" activity, respectively), as well as their difference, to illustrate the variations of the permitted lines and continuum during the period of our observations.

4.2. The Observed Optical Continuum

To represent the continuum of NGC 3783 in our optical spectra, we assumed that it can be described as a sum of, at least, two components: the bulge stellar population of the host galaxy and a power-law continuum ($F_ν = ν^{-α}$, with α positive and variable) (Begelman 1988; Stein & O'Dell 1985).

4.2.1. The Stellar Population Contribution at Low Activity

Using the off-nuclear spectra cited in § 2.2, we have determined the age and metallicity of the bulge stellar population of NGC 3783. This analysis has been described elsewhere (Winge et al. 1990), and here we will only summarize the relevant results: we have found that the stellar population of the galaxy bulge can be represented by the S4 template of Bica (1988) and is mainly old (82% of the flux at 5870 Å is due to a population older than 5 Gyr) with some contribution from intermediate-age and moderately young stars and of solar metallicity. We have also found that the emission-line ratios measured on the off-nuclear spectra indicate that the gas as far as 2 kpc from the nucleus is still photoionized by a power-law continuum.

Once we have obtained representation for the bulge stellar population the next step is to quantify its contribution to the nuclear spectrum. In previous works (Evans 1988; Ward et al.
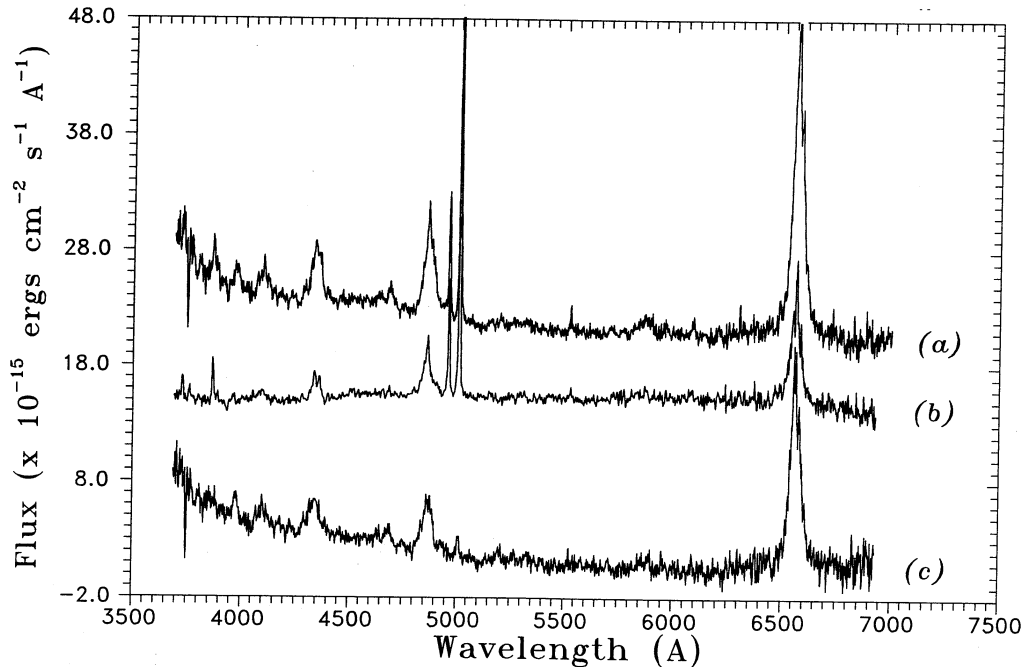
FIG. 4.—(a) High (run 8) and (b) low (run 2) states of NGC 3783 and (c) difference between them. Notice the strong variation in the continuum shape as well as intensity, and in the line fluxes.

1987) this contribution has been considered as negligible, due to the narrow slits and strong nonthermal (power-law) emission. However, as can be seen in Figure 5a, the run 2 spectrum is contaminated by the galaxy stellar population, presenting a flat or even positive slope, as well as the Ca II K and H $\lambda\lambda3933$, 3968 CH G band, Mg I + MgH $\lambda5175$ and Na I $\lambda5890$ absorption lines.

To have a first approach to the level of activity of the source at this epoch, we have collected the ratio $I(H\beta)/I([O\ III]\ \lambda4959)$ from the available literature, and the result including our own data is shown in Figure 6 as a function of time. It can be noted that the run 2 spectrum corresponds to a state of low activity of

the source, also observed in 1972, 1977, and 1981, and is characterized by a mean value of $I(H\beta)/I([O\ III]\ \lambda4959) = 2.1 \pm 0.4$.

Assuming that the run 2 spectrum represents the lowest level of activity reached by NGC 3783, the bulge stellar population contamination derived from this spectrum will represent the greatest contribution of the host galaxy to the nuclear light in this object, for the central 5″ × 5″.

To determine this contribution, the S4 template was normalized in order to represent 5% of the nuclear light at 5600 Å and repeatedly subtracted from the run 2 spectrum until the Mg I + MgH line was reduced to the noise level.
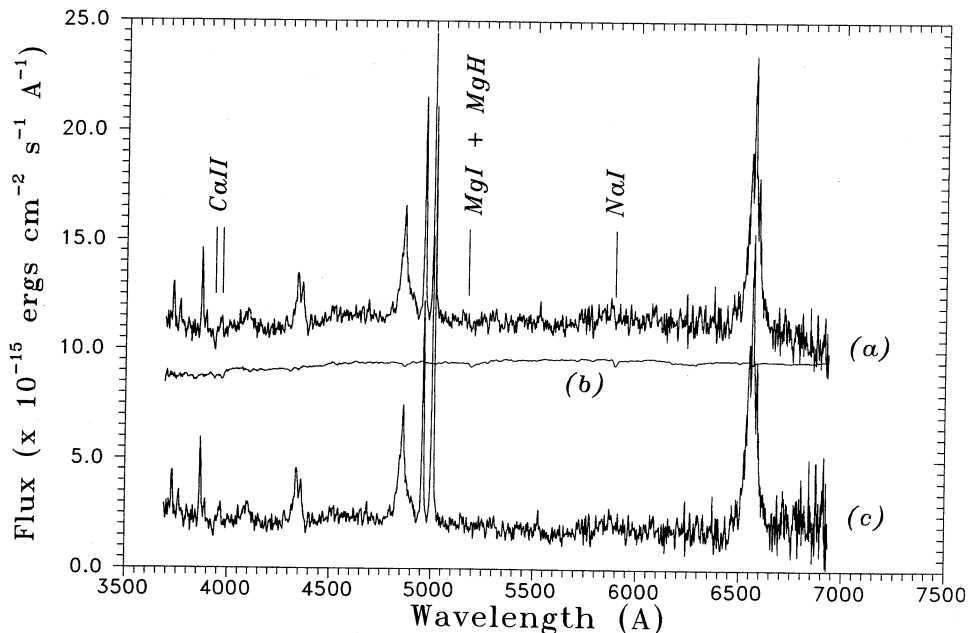
FIG. 5.—State of low-activity (run 2) spectrum before (a) and after (c) the subtraction of the bulge stellar population template (b) as described in the text. A constant has been added to spectra (a) and (b) for clarity.
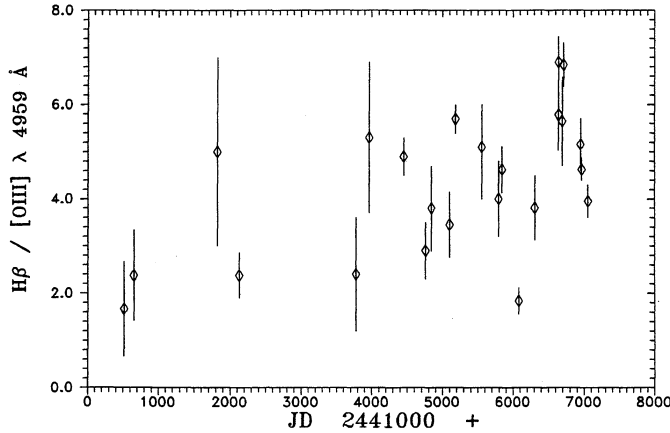
FIG. 6.—Hβ/[O III] λ4959 light curve for NGC 3783 from 1974 to 1990

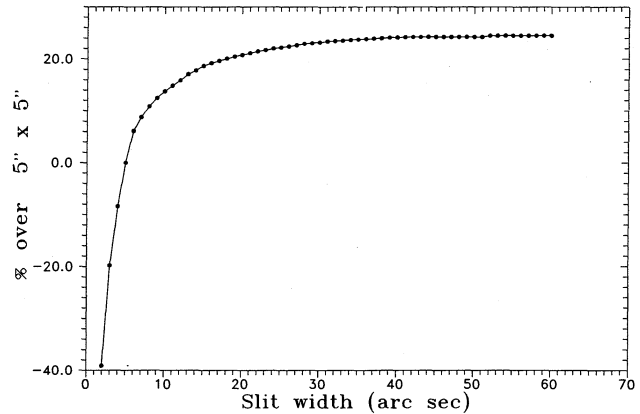

FIG. 8.—Dependence of the stellar population contribution with the dimensions of the slit, referred over the inner 5″ × 5″ contribution.

Figure 5c shows the nuclear spectrum after the subtraction of a stellar contribution correspondent to 50% ± 5% of the nuclear light at 5600 Å (shown in Fig. 5b). Notice the changes in the continuum shape and the emission lines (especially Hϵ λ3970).

We have then, obtained that the S4 template normalized to a flux of $F_\lambda = 1.566 \times 10^{-16}$ ergs cm^{-2} s^{-1} Å^{-1} at 5600 Å represents the total amount of stellar population contribution to the nuclear spectrum of NGC 3783 for a integration area corresponding to the central 5 × 5 arcsec².

4.2.2. Stellar Population Contribution for Different Slits

To derive an appropriate correction for the different areas encompassed by the slits used, we have considered that the flux of the continuum can be written, for any epoch,

$$\mathbf{F_{continuum} = F_{bulge} + F_{AGN}},$$

where $\mathbf{F_{bulge}}$ is the bulge stellar population contribution, dependent of the slit used, and of the bulge's light distribution, but constant in time.

$\mathbf{F_{AGN}}$ is the central source plus emission-line region contribution, variable in time but independent of the slit used.

The stellar population contribution to the total flux of each spectra was calculated from the spatial profile for 5600 Å, extracted from the 2D-FRUTTI original frame of run 2 (1988 May 10). This curve, presented in Figure 7, represents the

galaxy light distribution at λ5600, integrated over the 5″ of the slit width.

The next step was to integrate the central 5″ on the profile (which will correspond to the central 25 arcsec² emission) and normalize the resulting value to 100. With this procedure, we have determined that the contribution due to the nonthermal and stellar population components each amount to 50. Then, integrating the profile in successively greater areas (slits of 5″ × 6″, 5″ × 7″, etc.), and since the nonthermal contribution remains 50, we can construct the curve of Figure 8, which will be used to derive the stellar contribution for a given slit area, assuming that the stellar population is homogeneous (i.e., it can be represented on every point of the bulge by the S4 template). From this figure, we obtain the appropriate multiplicative factors that scale the stellar population contribution of the inner 25 arcsec² to each one of the different slit areas used. Notice that for those slits which include the total length of the galaxy, the saturation value of the curve, 24.5%, is used.

The scaling factors for the several spectra are presented in the second column of Table 3, and the third column gives the percentual stellar population contribution on each spectra for 5600 Å, with an error of order 5%.

4.2.3. The Nonstellar Continuum

Once the stellar population contribution was subtracted from all spectra, we have analyzed the nonstellar or featureless continuum, originated at the central source.

FIG. 7.—Spatial profile at 5600 Å, normalized as described in the text

TABLE 3

RESULTS FROM THE CONTINUUM ANALYSIS

Run (1)	Scaling Factor (2)	Percent at 5600 Å (3)	Spectral Index (4)
1.......	1.1087	41	1.5
2.......	1	50	1.2
3.......	1.3038	58	0.9
4.......	1.0447	37	0.7
5.......	1.0447	37	0.7
6.......	1.0447	36	0.4
7.......	1.0447	40	1.4
8.......	0.7717	29	0.7
9.......	1.0447	35	0.1
10.......	1.0447	32	0.7

Our work assumption was that this component can be represented by a power law

$$F_\nu = F_0 \nu^{-\alpha} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} ,$$

where α (the spectral index) and F_0 are positive constants, and that it would be the optical extension of the ionizing continuum, originating at the central source.

A least-squares fitting of the above function was done on a "spline" continuum traced over each spectra, for $\lambda > 5200$ Å, and the final solution was chosen as being the one that furnished the flattest spectrum and was below the observed data along all the spectral range.

The spectral indexes thus obtained are presented in Table 3. Taking into account the influence of the noise level of the spectra on the tracing of the spline continuum, an error of ± 0.1 has to be considered for these results. Figure 9 presents the spectra already free of the stellar population contribution, and the power-law continuum fitted for each epoch (hereafter referred as the PL continuum) is represented by the dashed line.

From this figure it can be seen the presence on all but two spectra (runs 2 and 9) of an excess above the PL continuum for wavelengths smaller than 5200 Å, with variable shape, intensity, and extension. Similar features, but of smaller intensity, have been found in NGC 7469 (Bonatto & Pastoriza 1990) and Mrk 590 (Ferland, Korista, & Peterson 1990).

For run 1, the emission at $\lambda < 3900$ Å above the PL continuum can be easily attributed to the high-order Balmer lines. However, for the other spectra where it is present, the excess is much too strong and/or begins at wavelengths too large to be produced by this same mechanism. The fact that the two simultaneous spectra of 1989 May (runs 4 and 5), obtained at different observatories under different conditions (detectors, slits, standard stars), are independently fitted by the same PL continuum and present the same blue excess makes us very confident of the reality of this feature.

Our first attempt to represent this excess was with a black-body curve, as the blue bump of AGN continua is frequently attributed to the emission by an accretion disk with $T \approx 20,000-35,000$ K (Malkan 1983; Stein & O'Dell 1985; Ulrich 1989). However, the continuum shape after the subtraction of the PL continuum cannot be represented at all by a Planckian function, and a simultaneous fit of a power law plus a blackbody over the entire range of the stellar population–free spectra continuum gives the same negative result.

As the emission-line fitting procedure (see § 3) is somewhat sensitive to the continuum level, it was necessary to find an analytical representation for the excess which allowed us to suitably remove the latter from below the emission-line spectrum. The simplest mathematical function which we found to represent appropriately the excess shape is another power law $F_\nu \propto \nu^{-\alpha}$, but now with negative spectral indexes.

We want to stress that the above function is a representation for the observed continuum shape: it cannot be extrapolated to wavelengths below the observed spectral range on each spectrum, and we do not want to attribute this specific form to any physical mechanism (as done with the PL continuum, that can be associated with the synchrotron emission from the central source). The only physical parameter that can be obtained from the fitting of a power law to the excess is the total flux of this feature.

The fit of the excess, when present, is also shown in Figure 9 as a dash-dotted line, as well as the final representation

for the nonstellar continuum in our spectra (i.e., PL continuum + excess) as a heavy line. For the sake of homogeneity we have chosen to decompose the emission on the run 1 spectrum by these same two components instead of trying to introduce another one for the high-order Balmer lines and continuum alone. We have then subtracted these components in order to isolate the pure-line emission.

4.3. *The Emission-Line Analysis*

The emission-line spectrum of quasars and Seyfert 1 nuclei is characterized by the presence of broad (full width at half-maximum [FWHM] $\geq 10^3$ km s^{-1}), frequently asymmetric, permitted lines which could present variability not only in flux, but also in profile (see Peterson 1988, and references therein).

To obtain a consistent representation for the emission line of our spectra (already free of all continuum contributions as described in §§ 4.2.2 and 4.2.3) we have first analyzed the variations in the line profiles, resulting from taking the difference between the various observations. This procedure is similar to the ones followed by Wamsteker et al. (1990) for NGC 5548 or Alloin, Boisson, & Pelat (1988) for Akn 120 and permits to isolate the individual variable components.

We have performed differences between all the CTIO and CASLEO spectra, that have similar resolutions, and a total of 17 differences presented variations with enough amplitude to permit an adequate decomposition in one or more Gaussian components, employing a method based on the technique described by Pelat & Alloin (1980) and used before by Bonatto & Pastoriza (1990).

The standard model (Table 4) obtained to describe the permitted lines of NGC 3783, is, then, composed of by no more than six components, defined in such a way that any other one was not necessary to fit any line in the entire set of spectra, although it was not necessary for all the components to be present on all the lines and/or all the spectra. The forbidden lines are represented by one or two Gaussians (the N- and I-components of the standard model). The doublets of the [Ne III] $\lambda\lambda3869, 3968$, [O III] $\lambda\lambda4959, 5007$, [O I] $\lambda\lambda6300, 6363$, and [N II] $\lambda\lambda6548, 6584$ lines are constrained to have the theoretical ratio of intensities and separation, and the same FWHM (in km s^{-1}). The [S II] $\lambda\lambda6717, 6731$ lines are constrained on theoretical separation and on equal FWHM. We first attributed only one component to each forbdden line, except the [O III] $\lambda\lambda4959, 5007$ lines. If the final fit is not satisfactory another component is included or the I-component of [O III] is suppressed. None of the fits accepts a third component for [O III].

The model constitutes the set of initial parameters furnished to the fitting routine: as a first guess, the six components are associated to each permitted line, with intensities estimated by eye, and central wavelengths and FWHM given by the model.

TABLE 4

STANDARD MODEL

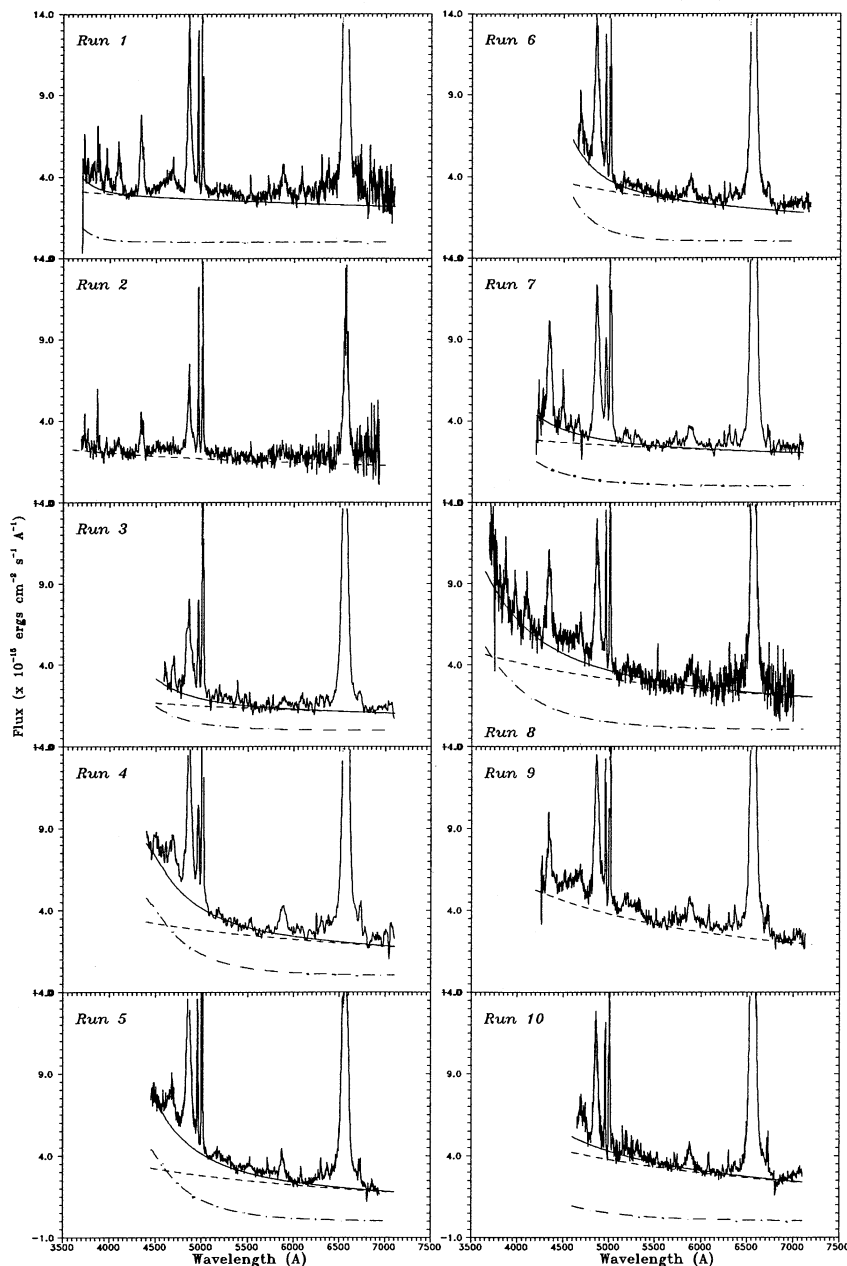| Component	Symbol	λ_0	FWHM (Å)
Narrow	N	Emission	[O III] lines
Intermediate	I	Emission	30
Broad	B	Emission	70
Very broad	VB	Emission	150
Blue wing	BW	Emission -20 Å	40
Red wing	RW	Emission $+40$ Å	60

FIG. 9.—The nonstellar continuum decomposition. The stellar population–free spectra are arranged in chronological order from top to bottom and from left to right. The dashed line is the PL continuum; the dash-dotted line is the power law fitted to the excess; and the solid line is the sum of these two contributions.

Once the convergence is achieved, or concluding by the inexistence of a local minimum on the reduced χ^2 for the guess, the results are examined, and any component that has diverged on FWHM or λ_0 away from the fitting region, or finalized with an intensity below the noise level, is excluded from the fit.

The entire procedure is repeated with the initial values of the standard model for the remaining components of the fit, until a reasonable representation has been obtained for the line profile (we have finalized with $\chi^2 < 0.5$ for all the lines and less than 0.01 for the majority of them).

The fitting regions are the following:

$\lambda\lambda 3700$–3750   [O II] $\lambda 3727$
$\lambda\lambda 3800$–3950   [Ne III] $\lambda 3869$, H8
$\lambda\lambda 3900$–4200   [Ne III] $\lambda 3968$ + Hϵ, Hδ
$\lambda\lambda 4250$–4450   Hγ + [O III] $\lambda 4363$

$\lambda\lambda 4400$–5200   He II $\lambda 4686$, Hβ, [O III] $\lambda\lambda 4959$, 5007
$\lambda\lambda 5600$–6150   He I $\lambda 5875$, [Fe VII] $\lambda 5721$, $\lambda 6085$
$\lambda\lambda 6250$–6800   [O I] $\lambda\lambda 6300$, 6363, [Fe X] $\lambda 6373$, Hα +
                  [N II] $\lambda\lambda 6548$, 6584, [S II] $\lambda\lambda 6717$, 6731.

All the lines within each of the above intervals were fitted simultaneously. An example of the resulting fit is given in Figure 10.

If the several components of the emission lines are supposed to originate at distinct subregions inside the emission-line regions (ELRs), each of these subregions could be characterized by the velocity of turbulence of the gas ($v_t \equiv$ FWHM of the Gaussian component/1.67) and by the shift of the central wavelength of the component with respect to the systemic velocity of the galaxy (hereafter $\Delta\lambda$).

In order to isolate these subregions we have plotted the
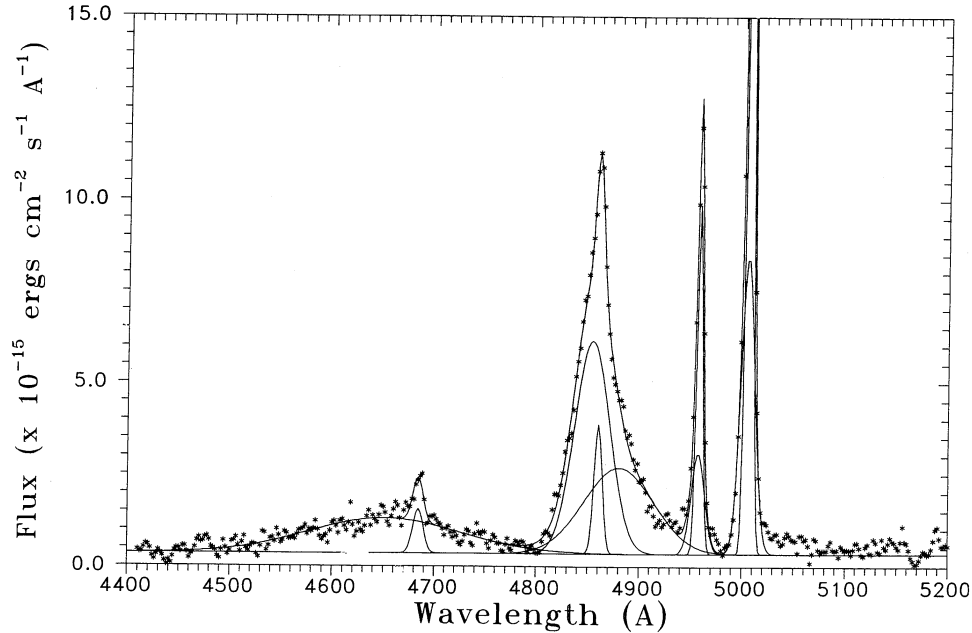
FIG. 10.—Example of the Gaussian decomposition for the He II λ4686 + Hβ + [O III] λλ4959, 5007 lines on the run 1 spectrum

FWHM of the components as a function of their Δλ for all the emission lines on each spectrum, as illustrated on Figure 11 for the run 8 spectrum. The points clearly segregate in four main regions.

When plotting the FWHM versus Δλ of the components of each permitted line, considering simultaneously all the observations, three regions are found. This result is illustrated in Figure 12a and less clearly (due to the smaller S/N of the emission lines that affects the final solution of the Gaussian decomposition) in Figures 12b and 12c.

The analysis of these figures permits us to establish the characteristics for the regions shown in Table 5.

Comparing Figures 12a an 12b, it can be noted that besides

the main regions observed both in Hα and Hβ, for the latter we have several components with turbulent velocities between 1500 and 3700 km s^{-1} and wavelength shifts usually greater than 1000 km s^{-1} both to the blue and red sides of the systemic velocity. These components, which we have called *transient components*, if associated with a different region (or regions), will correspond to emission by a gas with $N_e > 10^8$ cm^{-3}, as they have not been detected on the forbidden line profiles.

Tables 6 and 7 present the results of the line analysis. Table 6 gives the mean narrow-line fluxes (sum of regions 1 and 2, averaged over all the observations) and Table 7, the broad-line ones (sum of regions 3, 4 and transient components, for each epoch). The values are given in units of 10^{-15} ergs cm^{-2} s^{-1},
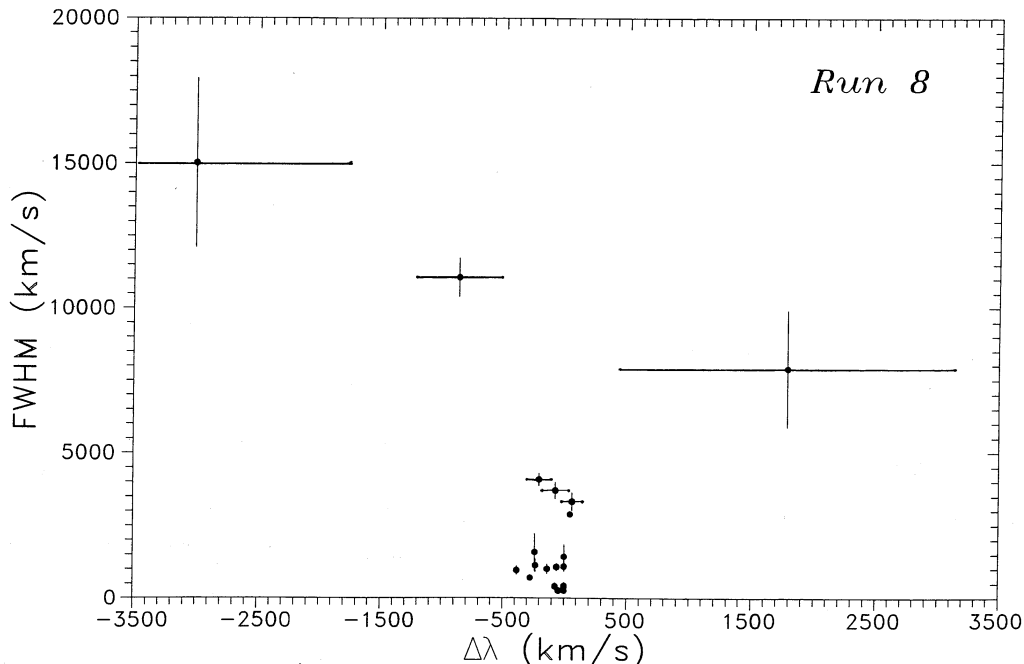
FIG. 11.—FWHM vs. Δλ plot for all lines fitted on the CTIO run 8 spectra
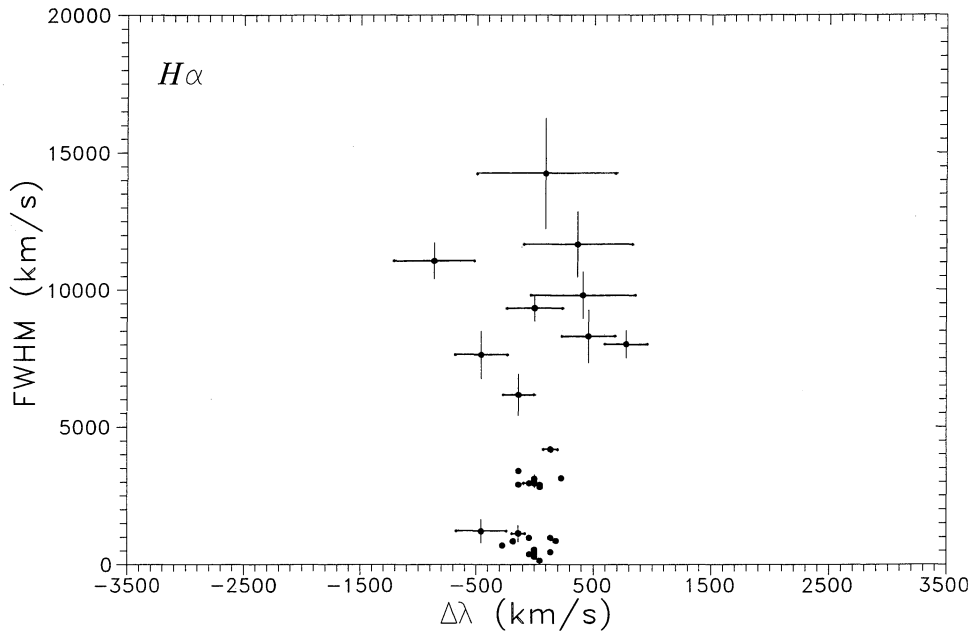
FIG. 12a
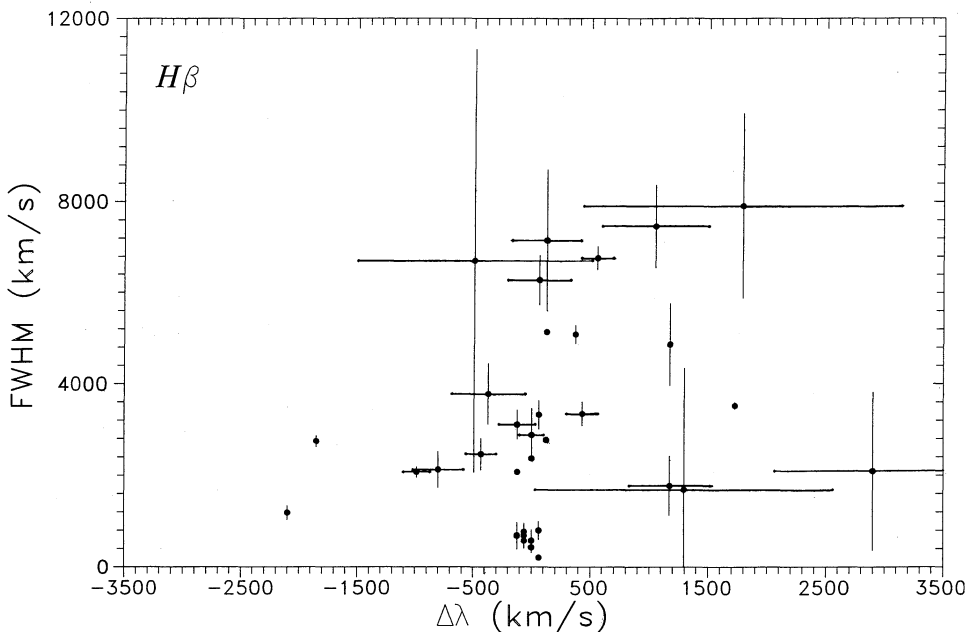
FIG. 12b

FIG. 12.—Same as Fig. 11, but for the components fitted to the permitted lines on the entire set of spectra. (a) Hα (b) Hβ, and (c) He II λ4686.

and the errors are calculated from the standard deviation furnished by the fitting routine for each component, with a different weight given by the percentage contribution of the component to the total flux of the line.

Although the decomposition method employed here does not assure the physical reality of the emission-line subregions, the homogeneity on the parameters found for the components of the different lines corresponding to the four main regions seems to indicate that the gas responsible for their emission indeed constitutes separate systems.

4.4. The NLR Physical Conditions and Abundances

In this section we will analyze the NLR contribution, characterized by regions 1 and 2 (components N and I of the standard model). Since the resolution of some spectra does not allow us to resolve these two components, we have considered in what follows the total NLR contribution represented by the sum of regions 1 and 2. This contribution will be referred to, hereafter, as the R12 emission.

First, we have verified the possibility of narrow-line variabil-
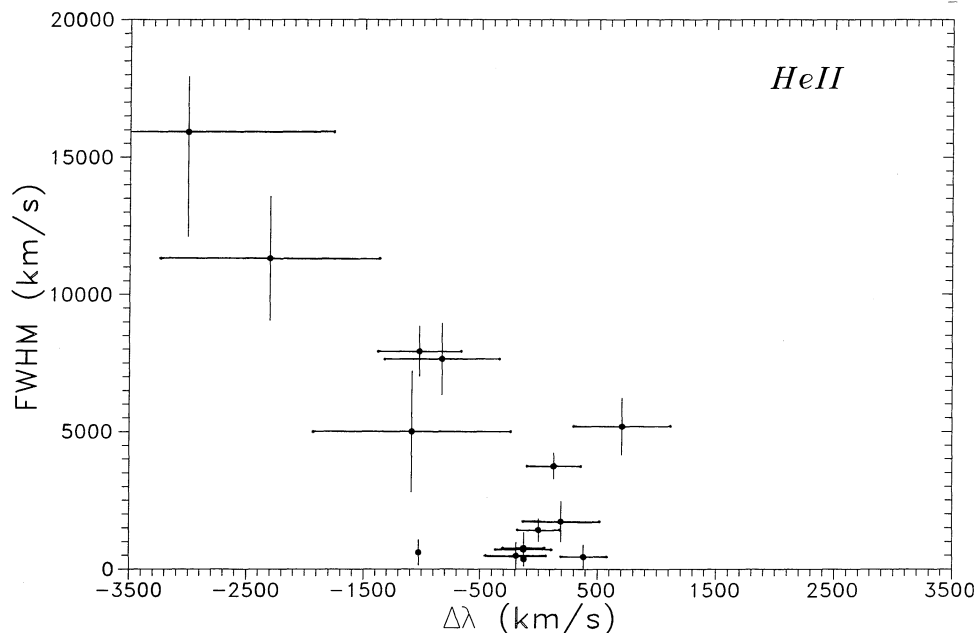
FIG. 12c

ity, and we found that the forbidden line fluxes agree within the measurement errors, even for the [Fe x] $\lambda\lambda6373$ line, thought to have already presented variability (Evans 1989). We have also verified that the intensities of the forbidden lines relative to that of [O III] $\lambda4959$ are consistent with previously published data (Evans 1988, 1989; Atwood et al. 1982). Therefore, we can extend the conclusion of Evans (1989), whose 1983 and 1984 spectra show forbidden line fluxes (relative to [O III] $\lambda4959$) consistent with previous data obtained over 10 yr from then, indicating no narrow-line variability, and assert that the time scale for emission-line variation on the NLR is at least 16 yr.

In order to calculate the physical conditions inside the R12, we have used the averaged fluxes of Table 6. From these values, we get the Balmer decrement Hα/Hβ = 3.6 $\pm$ 1.8, indicating few or no internal absorption on the R12 clouds, as already discussed by Ward & Morris (1984).

The electronic temperature and density are calculated using the three-level atom approximation of McCall (1984) for the [O III] $I(\lambda4959 + \lambda5007)/I(\lambda4363)$ and [S II] $I(\lambda6717)/I(\lambda6731)$ ratios. Using the [S II] ratio, we get for the density,

$$Ne = 2100^{+1300}_{-800} \text{ cm}^{-3} .$$

In the calculation of the temperature we have to consider the influence of the stratification in electronic density known to be present in the NLR of NGC 3783 (Pelat et al. 1981; Evans 1988). The critical density for collisional de-excitation for the [O III] lines is much higher than that of the [S II] lines, and the bulk of its emission comes from regions with densities near the critical value, that is, near 10^6 cm^{-3}. We have used this value (see also Storchi-Bergmann, Bica, & Pastoriza 1990) to obtain a temperature for the R12 of

$$T_e = 13200^{+1200}_{-2700} \text{ K} .$$

The ionic and He abundances are calculated using the above electronic density and temperature with the expressions of McCall (1984) for the ions, and Osterbrock (1974) for the recombination lines of He$^+$ and He^{++}, with an adequate correction from Ferland (1986) to account for the collisional excitation of He I $\lambda5875$. The results are shown in Table 8, and from them we can obtain a 2 times solar abundance of nitrogen and a one-third solar abundance of oxygen for the NLR of NGC 3783. Overabundance of nitrogen has been already found in the BLR of NGC 3783 by Koratkar (1990), and in Seyfert 2 galaxies by Storchi-Bergmann & Pastoriza (1989).

TABLE 5

MAIN REGIONS CHARACTERISTICS

Region	v_t (km s^{-1})	$|\Delta\lambda|$ (km s^{-1})	N_e (cm^{-3})	Lines Present
1.........	≤ 500	≤ 300	$\leq 10^6$	[O I], [O II], [N II], [S II], [Ne III], Balmer lines, He I, He II, and [O III] narrow components
2.........	500–1000	≤ 700	10^{6-8}	[Fe VII], [O III], [O I], Balmer lines, He I, He II intermediate components
3.........	1800–2000	≤ 700	$\geq 10^8$	Balmer lines, He I broad components
4.........	≥ 4000	≤ 3500	$\geq 10^8$	Balmer lines, He I, He II very broad omponents

TABLE 6

MEAN R12 FLUXES[a]

[O ii] λ3727	22.5 ± 5.3
[Ne iii] λλ3869, 3968	45.3 ± 7.1
Hδ λ4101	10.0 ± 4.3
Hγ λ4340	16.3 ± 6.0
[O iii] λ4363	15.1 ± 6.1
He ii λ4686	18.2 ± 9.3
Hβ λ4861	35.8 ± 10.9
[O iii] λλ4959, 5007	421.4 ± 9.6
[Fe vii] λ5721	9.0 ± 0.9
He i λ5875	8.7 ± 7.9
[Fe vii] λ6085	20.7 ± 3.3
[O i] λλ6300, 6363	25.9 ± 2.8
[Fe x] λ6373	8.8 ± 5.7
Hα λ6563	134.4 ± 17.3
[N ii] λλ6548, 6584	40.3 ± 6.1
[S ii] λ6717	11.3 ± 2.7
[S ii] λ6731	14.0 ± 1.5

[a] In units of 10^{-15} ergs cm^{-2} s^{-1}.

5. SPECTRAL VARIABILITY

In this section we do not intend to do an accurate analysis of the spectral variability in NGC 3783, since our observations do not provide an adequate coverage of the galaxy light curve. However, some interesting characteristics of the variations can be obtained from our data.

The light curves for Hα and Hβ lines are shown on Figures 13a and 13b for the total flux of the BLR (i.e., the total flux of the line, excluded the contribution from the N- and I-components) and for the B- and VB-components separately.

It is interesting to point out the presence of two epochs where the variations in the fluxes of these lines occur in different senses: from run 5 to run 6, Hβ remains constant while Hα decreases, and from run 9 to run 10 Hβ decreases while Hα increases. When analyzed in terms of the components, this behavior is seen to be due to the Hβ VB- and transient components, since the light curve for the B-component is similar for both lines.

The overall shape of the Hα line does not vary substantially during the observations, as can be noted considering the FWHM versus $\Delta\lambda$ plot for this line (Fig. 12a). The components are concentrated around zero wavelength shift, and the dominance of the B-component which responds by about 65% of the line flux, as well as the absence of transient components guarantees an almost steady line profile.

TABLE 8

NLR ABUNDANCES

Identification	Value
He/H	0.206 ± 0.336
$12 + \log (O^{++}/H^+)$	$8.24^{+0.13}_{-0.17}$
$12 + \log (O^+/H^+)$	$7.10^{+0.17}_{-0.30}$
$12 + \log (O^0/H^+)$	$7.72^{+0.23}_{-0.56}$
$12 + \log (O/H)$	$8.38^{+0.08}_{-0.10}$
$\log (O^+/N^+)$	$0.09^{+0.17}_{-0.28}$
$12 + \log (N/H)$	$8.29^{+0.17}_{-0.26}$
$12 + \log (S^+/H^+)$	$6.07^{+0.20}_{-0.40}$
$12 + \log (Ne^{++}/H^+)$	$7.65^{+0.15}_{-0.22}$

The Hβ profile on the other hand, is strongly asymmetric and varies in a rapid and drastic way. These variations are mainly due to the presence of the transient components, which, together with the VB-component are responsible by the bulk of the flux on this line, and present a wide scatter on the FWHM versus $\Delta\lambda$ plane (see Fig. 12b).

Finally the He ii λ4686 line (Fig. 12c) presents the peculiarity of not admitting a clearly separated B-component on the emission-line decomposition, besides having a VB-component shifted to the blue side of the line, while all the other permitted lines show this component centered on the systemic velocity or shifted to the red wing. The first characteristic was also detected in NGC 5548 by Wamsteker et al. (1990) and interpreted by them as an evidence of a stratification in excitation and in gas velocity in this galaxy. The second one can be attributed to the presence of the N iii λ4640 lines (Stirpe et al. 1988) or of the Fe ii multiplets 37 and 38 (λλ4500–4600). The Fe ii emission is historically very weak in NGC 3783 (Steiner 1981; Pelat et al. 1981; Barr et al. 1983; Evans 1988), but the stronger multiplet 42 ($\approx$λ5200) is quite evident in the spectra of runs 5–10. We can tentatively associate the surgiment of these features as a response to the strong burst that occurred in 1989 (runs 4 and 5: Winkler & van Wik 1989).

In what follows we will refer to as the "excess" the residual continuum emission found on eight of our 10 spectra, after the subtraction of the PL continuum. As can be seen in Figure 9, the temporal behavior of the total continuum for λ < 5000 Å is strongly dependent on the behavior of the excess.
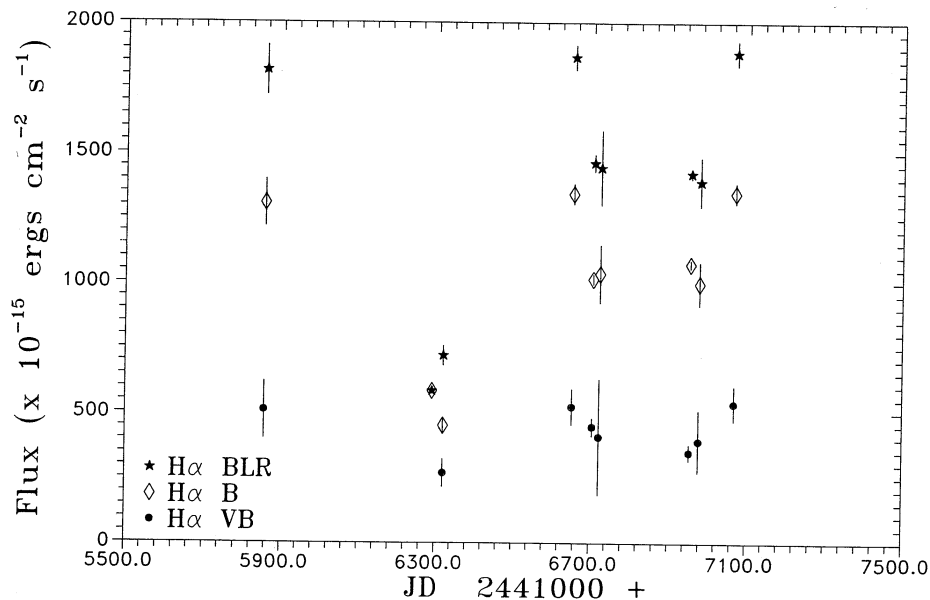
TABLE 7

BLR FLUXES[a]

IDENTIFICATION	RUN									
	1	2	3	4	5	6	7	8	9	10
Hδ	96	43	...	...	...	...	...	90	...	...
λ4101	16	19	...	...	...	...	...	11	...	...
Hγ	197	62	...	...	...	...	...	175	116	...
λ4340	31	30	...	...	...	...	...	16	15	...
He ii	164	...	8.4	159	191	146	...	192	238	...
λ4686	47	...	11	24	51	39	...	51	76	...
Hβ	409	201	296	475	465	531	445	472	546	439
λ4861	66	44	13	26	52	50	3	63	54	100
He i	219	137	...	144	152	136	58	...	226	130
λ5875	54	41	...	43	40	84	43	...	43	37
Hα	1816	584	720	1867	1851	1462	1444	1422	1390	1883
λ6563	96	11	38	47	103	34	143	20	94	48

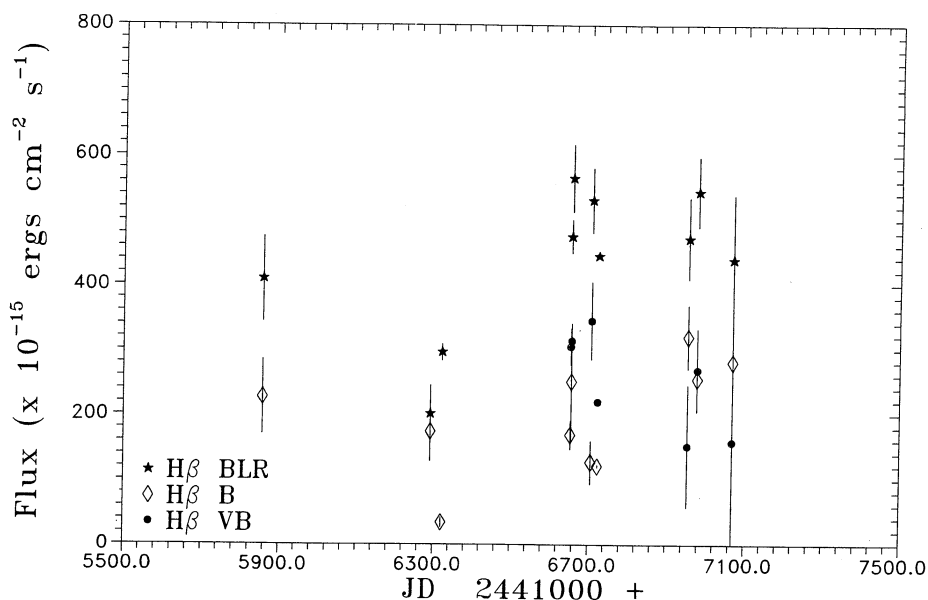[a] In units of 10^{-15} ergs cm^{-2} s^{-1}.

Fig. 13a

Fig. 13b

Fig. 13.—Light curve for the total BLR flux, B- and VB-components of (a), Hα, and (b) Hβ. Notice that runs 4 and 5 correspond to the same point in a.

To describe the behavior of the ionizing continuum and the overall shape of the spectra, we define: the following: $F(5600/1450)$: flux ratio $F(\lambda 5600)/F(\lambda 1450)$ calculated from the PL continuum analytical form, used to represent the hardness of the ionizing continuum; F_{EX}: integrated flux of the excess, between 4650 and 7100 Å.

We now analyze the possible correlations between these two parameters and between them and the BLR fluxes. In Figure 14 is shown the dependence of the Hβ BLR flux with $F(5600/1450)$. There is a linear correlation, in the sense that the line flux is greater when the spectrum is "harder." However, there are two points that deviate from this general behavior, corresponding to runs 1 and 7. The deviation of the run 7 point

could be tentatively attributed to a delay in the overall line response to fast falls of the ionizing continuum, such as the one which occurred between runs 6 and 7 (the power-law index turns from $\alpha \approx 0.4$ to 1.4 in 18 days). If the behavior of the first point is also attributed to a similar delay of the emission-line gas response to continuum variations that occurred before our first observation (see Stirpe et al. 1988), and these epochs are taken as anomalous and excluded from the fit, the linear correlation between Hβ(BLR) and $F(5600/1450)$ is significant at an $R = 0.97$ level. Similar relations, but of lower significance, are found for the BLR fluxes of Hα, He I $\lambda 5875$, and He II $\lambda 4686$ ($R = 0.63$, 0.85, and 0.82, respectively), with the same two points deviating on all of them. These facts seem to indicate
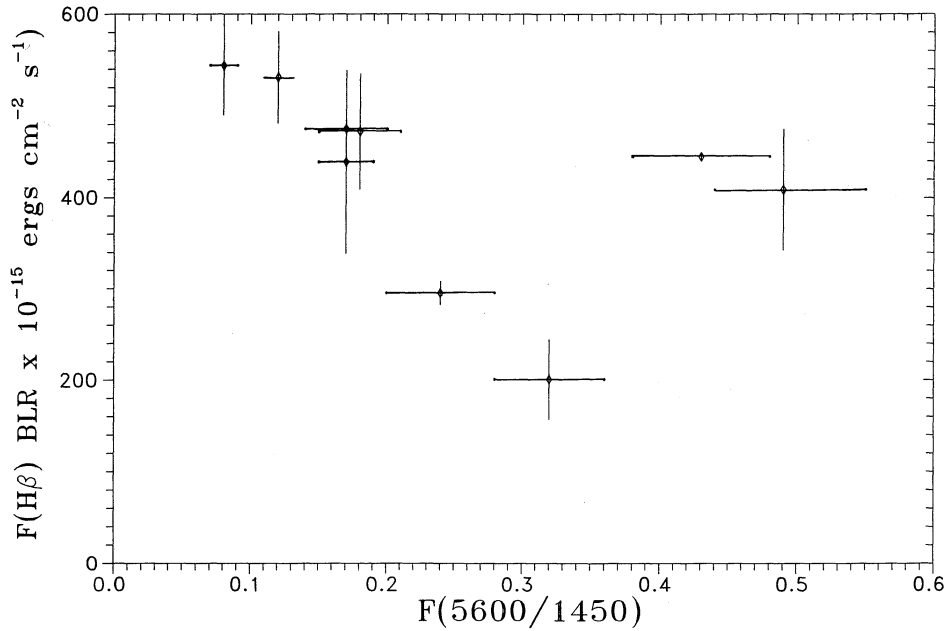
FIG. 14.—Correlation between the BLR flux of Hβ and the flux ratio of the PL continuum

that the PL continuum can be actually interpreted as the optical tail of the ionizing one. Simultaneous UV-optical observations are necessary to confirm this evidence.

On the other hand, none of the lines shows any correlation with F_{EX}. This, together with the similarity of the dependence of the integrated flux on the excess with $F(5600/1450)$ (Fig. 15) with that of the lines, leads us to suppose that the continuum emission that constitutes the excess is generated at the BLR and driven by the ionizing continuum of the central source in a similar way to the emission lines.

Considering all the BLR emission, the Balmer decrement varies between

$$2.5 \pm 0.3 \leq H\alpha/H\beta \leq 4.7 \pm 0.3 \; .$$

Considering the total flux of the lines, the luminosity on the period covered by our observations varied by 220% for Hα, 160% for Hβ, and 2300% for He II λ4686, relative to the state of low activity characterized by run 2. In terms of luminosity we have

$$2.42 \times 10^{41} \leq \mathscr{L}(H\alpha) \leq 7.71 \times 10^{41} \; \text{ergs s}^{-1} \; ,$$

$$8.86 \times 10^{40} \leq \mathscr{L}(H\beta) \leq 2.25 \times 10^{41} \; \text{ergs s}^{-1} \; ,$$

$$3.78 \times 10^{39} \leq \mathscr{L}(\text{He II}) \leq 9.09 \times 10^{40} \; \text{ergs s}^{-1} \; .$$

Using the variations on the luminosity of Hβ, we calculated the variation on the number of ionizing photons that reaches
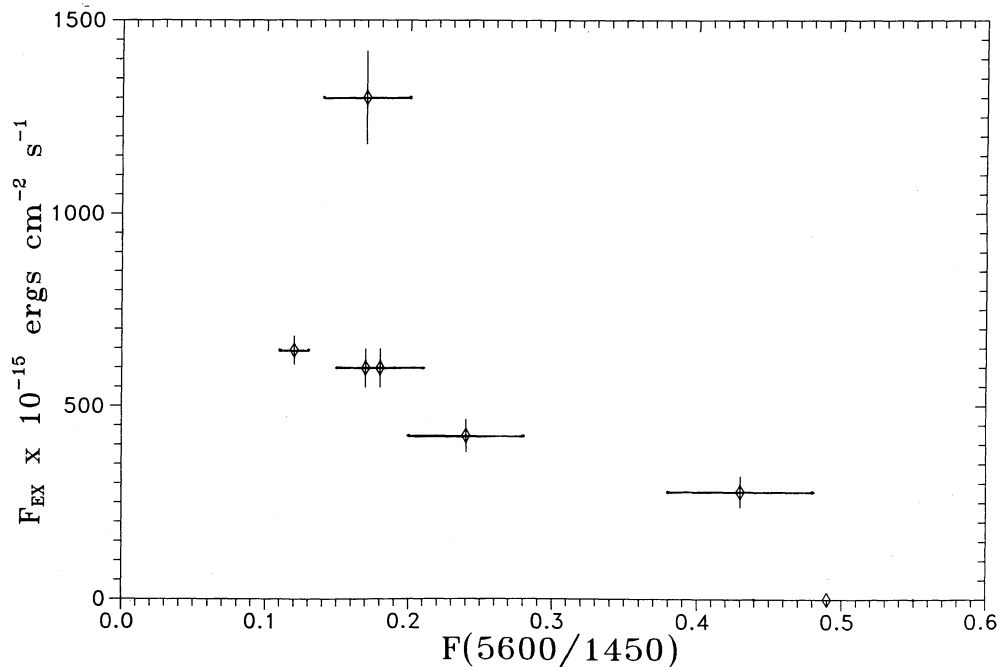
FIG. 15.—Same as Fig. 14, but now for the integrated flux on the excess