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BROAD-LINE VARIABILITY IN NGC 3783

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ABSTRACT

New intermediate-resolution optical spectrophotometry of the nucleus of the southern Seyfert 1 galaxy NGC 3783 is presented. These data are compared with previously published data to study the variations in the intensities and profiles of the broad emission lines. The intensities of the broad Balmer lines have decreased by a factor of ~ 2 between 1983 May and 1984 March. The Balmer decrement derived from the 1983 May data is substantially flatter than for the later data, and the profiles of the broad Hα and Hβ emission lines have varied independently, indicating that emission from multiple line components with different Balmer decrements must contribute to the overall line emission. Comparison of the observations with published photoionization models for quasar and Seyfert broad-line clouds suggests that the variability can be explained in terms of a model in which both the incident ionizing flux and the optical depth in the emitting clouds varies.

Subject headings: galaxies: individual (NGC 3783) — galaxies: nuclei — galaxies: Seyfert — line profiles — spectrophotometry

I. INTRODUCTION

The bright southern Seyfert 1 galaxy NGC 3783 has been the subject of several recent investigations. Optical spectrophotometry of the nucleus has been obtained at low and intermediate resolutions by a number of authors (e.g., Martin 1974; Osmer, Smith, and Weedman 1974; Penston *et al.* 1977; Ward 1978; Ward and Morris 1984; Morris and Ward 1988), and at higher resolution by Pelat, Alloin, and Fosbury (1981) and Atwood, Baldwin, and Carswell (1982). Recently, Evans (1988) presented detailed high signal-to-noise, high-resolution spectrophotometry covering most of the optical waveband, and used these data to extend the earlier work of Pelat, Alloin, and Fosbury (1981) studying the profiles of the broad and narrow emission lines for a wide range of ionic species and transitions.

A high degree of nuclear continuum variability in both the optical and infrared has long been recognized for this object (Glass 1979; Penfold 1979), while a comparison of published intermediate-resolution spectrophotometry indicates that the broad Balmer-line intensities also vary with time. Observations by Menzies and Feast (1983), and more recently by Stirpe, de Bruyn, and van Groningen (1988), confirm this broad-line intensity variability and demonstrate that the broad-line *profiles* are also variable.

In this paper, new intermediate-resolution optical spectrophotometry of the nucleus of NGC 3783 is presented. These data demonstrate that the nucleus was in a very luminous state in 1983 May, manifested through considerably enhanced broad-line and optical continuum emission, compared to the quiescent state evident in the data of Evans (1988), which were obtained in March of 1984. The two data sets are compared to derive the relative strengths of the continuum and broad-line intensities, and profile ratios are constructed for the Hα and Hβ Balmer lines to detect differences in the line profiles between the two epochs.

II. OBSERVATIONS AND REDUCTIONS

The optical spectra were obtained under nonphotometric conditions at the 3.9 m Anglo-Australian Telescope on the night of 1983 May 12–13. The Royal Greenwich Observatory spectrograph was used with the image photon counting system (IPCS; Boksenberg 1972) as a detector. The instrumental configuration was chosen to give 64 spectra, each separated by 1".15 on the sky, with a spectral resolution of 5 Å and a spectral coverage of 3200–7400 Å. A slit width of 300 μm (2".01 on the sky) was employed for these observations. An integration time of 2000 s through a neutral 1.0 density quartz filter (10% nominal transmission at 6000 Å) was used to obtain the data. During the exposure, the seeing varied between 1".5 and 2".0. The spectrograph slit was centered on the nucleus of the galaxy, with a slit position angle of 54° chosen to avoid significant extended emission from the bar of NGC 3783.

The spectra were reduced by the following procedure. First, pixel-to-pixel variations in the response of the detector were removed by division of the data by a normalized flat field obtained by summing six long exposures of an unfiltered tungsten lamp in third-order red. Second, each spectrum was rebinned to a linear wavelength scale by making a two-dimensional fifth-order polynomial fit to the calibration arcs. Third, a wavelength-dependent multiplicative correction factor was applied to each of the spectra to account for the transmision of the neutral-density filter. Finally, the spectra in the six spatial increments along the slit (6".9 on the sky) centered on the nucleus were summed with weights determined by the signal-to-noise ratio, and the mean of the spectra extracted from the 18 spatial increments located 9".2–29".9 on the sky on either side of the nucleus was then appropriately scaled and subtracted from the summed nuclear spectrum to correct for the underlying background emission.

Since the data were obtained under nonphotometric conditions, the spectra could not be converted to absolute flux in the usual manner. Instead, a correction for the relative wavelength dependence of atmospheric extinction and detector sensitivity was applied based on observations of Oke (1974) white dwarf standard stars. An absolute flux calibration was applied by computing the weighted mean gray shift required to bring the observed fluxes of the optical forbidden lines (which are assumed *a priori* not to vary on time scales of about a year)

TABLE 1

Optical Line Intensities

Line	$I_{\mathrm{This\ Paper}}$	$I_{\mathrm{Evans\ (1988)}}$
[Ne v] λ3346	8.7 ± 2.4	10.29
[Ne v] λ3426	34.0 ± 2.3	28.68
[O II] λ3727	12.6 ± 1.3	13.65
[Fe VII] λ3760	5.1 ± 1.9	8.27
[Ne III] λ3869	27.6 ± 3.0	21.76
He I λ3889, Hζ λ3889	11.5 ± 1.3	13.14
[Ne III] λ3968, Hϵ λ3970	50.1 ± 5.8	25.92
Hδ λ4102	91.8 ± 9.8	40.56
Hγ λ4340, [O III] λ4363	178.4 ± 7.8	73.11
He II λ4686	157.6 ± 7.1	21.29
He II λ4686 (narrow)	11.3 ± 5.3	6.12
Hβ λ4861	490 ± 15	294.1
[O III] λ4959	100.0 ± 6.0	100.00
[O III] λ5007	312.8 ± 7.9	(419.8)[a]
[Fe VII] λ5721	9.3 ± 1.4	8.20
He I λ5876	75 ± 16	44.94
He I λ5876 (narrow)	5.8 ± 2.3	4.18
[Fe VII] λ6086	15.9 ± 3.8	15.00
[O I] λ6300	18.4 ± 3.7	24.06
[O I] λ6364, [Fe X] λ6375	20.9 ± 6.2	46.53
Hα λ6563, [N II] λλ6548, 6584	1614 ± 27	1885.7
[S II] λ6716	8.1 ± 2.1	10.27
[S II] λ6731	13.7 ± 3.0	12.21

[a] IPCS data saturated.

into agreement with those derived from the high-resolution, high signal-to-noise spectrum obtained in 1984 March (Evans 1988). The weighting applied to the gray shift estimate from each forbidden line used to compute the mean gray shift was determined by the signal-to-noise ratio in the line, with the exceptions of [O III] λ5007 and [Fe X] λ6375 which were given zero weighting. The former was saturated in the data of Evans (1988) and hence could not be used to derive a gray shift, while the latter differed substantially with the weighted mean derived from the other forbidden lines, suggesting that this line may actually have varied in intensity between the two epochs (see § III below). Comparison of the relative fluxes of the forbidden lines between the two sets of data, as a function of wavelength, indicates that the flux calibration should be accurate for data redward of ∼3600 Å, but is somewhat poorer for shorter wavelengths (see Table 1). Since the observations were made with a nonparallactic slit position angle (the mean parallactic angle during the observations was 86°) and with airmasses ranging from 1.20 to 1.31, it seems plausible that differential atmospheric refraction and differential extinction corrections may be the most probable causes for the decreased quality of the flux calibration at the shorter wavelengths. No reddening corrections have been applied to the data.

III. RESULTS AND DISCUSSION

Comparison of these data with those of Evans (1988), which were taken approximately 10 months later, demonstrates the dramatic changes which can occur in the broad-line fluxes and the continuum level on time scales of a few months. The 1983 May spectrum is shown in the upper panel of Figure 1, together with the 1984 March spectrum (Evans 1988) for comparison. (The latter has been convolved with a Gaussian blurring function to yield the same effective resolution as the 1983 May data.) The difference between the two sets of data is shown in the lower panel of the figure. Inspection of the figure clearly illustrates the increased broad-line fluxes and continuum level evident in the earlier data. The observed line intensities relative to $I([\mathrm{O\ III}]\ \lambda4959) = 100$ are presented in Table 1, together with the intensities derived from the multiple Gaussian profile fits to the 1984 March data from Evans (1988). For the latter, the typical error is less than ∼2% of the line intensity. The λ4959 line of [O III] is used as the basis for computing the relative line fluxes, rather than λ5007, because the latter line is saturated in the 1984 March spectrum.

The data presented in Table 1 illustrate that the intensities of the narrow emission lines redward of 3600 Å, measured relative to [O III] λ4959, agree to within the 3 σ errors between the two sets of data. This shows that these lines have not varied significantly relative to each other on this time scale. This is also true for the narrow components of the He I λ5876 and He II λ4686 lines, which are the only two lines in the present data set which show clearly distinct narrow and broad components. The narrow emission-line ratios relative to [O III] λ4959 are also consistent with the earlier spectrophotometry of Martin (1974), Penston *et al.* (1977), and Atwood, Baldwin, and Carswell (1982), and also with the spectrophotometry of Ward and Morris (1984) redward of ∼4000 Å, implying that the time scale for variation of the narrow emission lines is at least 10 yr. However, the narrow-line data do not agree with the measurements of the latter paper in the far blue region of the spectrum, where the authors derive line intensities for the strong [Ne v] λ3426, [O II] λλ3726, 3729 doublet, and [Ne III] λ3869 lines which are a factor of ∼3 times stronger, relative to [O III] λ4959, than those measured from the high signal-to-noise data of Evans (1988). One possible explanation for this discrepancy may be a less than certain calibration of the Ward and Morris (1984) data blueward of Hδ (their spectra "D" taken in 1977 July), since, as they indicate in that paper, those spectra were not flux calibrated but were normalized based on comparison of the intensity of the blue continuum with the observations of their spectra "C" which were taken almost 5 yr later in 1982 January. The measured narrow-line intensities for the [O II] λλ3726, 3729 doublet and the [Ne III] λ3869 line also disagree with the measurements of Morris and Ward (1988) which are, respectively, ∼2 times and ∼3 times larger than the values derived from the data of Evans (1988), although the intensities of the other strong narrow lines (including [Ne v] λ3426) agree to within the errors. There is no clear explanation for these differences, although the choice of the continuum placement or aperture size may contribute.

Comparison of the broad Balmer lines indicates substantial differences between the two epochs. The intensities of the broad Balmer lines derived from the data presented here are, with the exception of Hα, all considerably stronger than those measured by Evans (1988). The relative strengths of the Balmer-line intensities in 1984 March relative to 1983 May vary from ×0.86 for Hα through ×1.67 for Hβ, ×2.8 for Hγ, and ∼×2.2 for both Hδ and Hϵ, indicating that the Balmer decrement derived from the current data is substantially flatter than at the later epoch. The relative strengths of the Balmer-line intensities listed above were computed after correcting for the contributions from the contaminating forbidden lines ([N II] λλ6548, 6584 for Hα, [O III] λλ4959, 5007 for Hβ, [O III] λ4363 for Hγ, [S II] λλ4069, 4076 for Hδ, and [Ne III] λ3969 for Hϵ) assuming that the intensities of the narrow lines did not vary between the two epochs. The forbidden-line intensities used to correct the Balmer-line data were those measured from the 1984 March spectrum (Evans 1988).

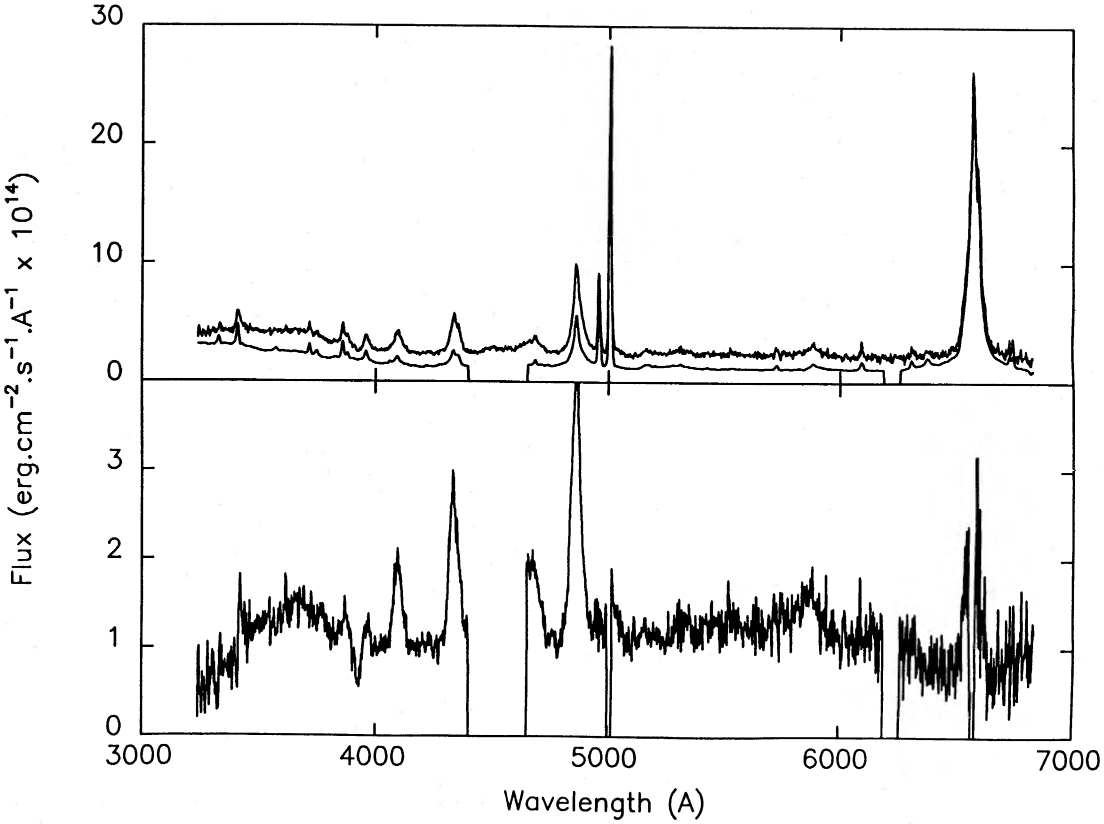

FIG. 1.—The nuclear spectrum of NGC 3783 is presented in the upper panel. The upper trace indicates the data presented here, while the lower trace indicates the date of Evans (1988) smoothed to the same spectral resolution. The difference between the two spectra is shown in the lower panel of the figure.

For a given set of physical conditions (electron temperature, density, and ionization parameter) in the emission regions, atomic physics constrains the relative strengths of corresponding Balmer lines in the two spectra to be a smoothly varying monotonic function of position in the Balmer series. Even when the physical conditions are varied over a relatively wide range, this tends to remain true, provided that none of the level populations are inverted, and provided that the reddening does not change significantly between the two sets of observations. This latter possibility will be ignored in the discussion that follows, although it cannot be completely excluded. The consistency of the narrow emission-line data implies that any changes in reddening which may have taken place must have occurred interior to the narrow-line region, possibly as a result of dust mixed in with the broad-line gas

With the exception of Hγ, the relative strengths of corresponding broad Balmer lines are indeed a monotonic function of position in the Balmer series to within the measurement errors. The derived relative change in intensity for the Hγ line is too large in comparison with the surrounding Balmer lines. However, the entire Hγ–[O III] λ4363 region is strongly contaminated by underlying Fe II emission from multiplets 27 and 28. The profiles of the Fe II lines are observed to have similar shapes to the broad Hβ profile in a number of objects (e.g., Osterbrock 1977; Phillips 1977, 1978; Oke and Lauer 1979), indicating that the Fe II emission arises in gas near the Balmer-line emitting region in the broad-line clouds. This suggestion is also confirmed by the theoretical calculations of Netzer (1980) and Netzer and Wills (1983). Hence one would expect that the Fe II emission should react in phase with the broad Balmer lines to changes in the ionizing spectrum from the central source. Unfortunately, it is not possible to estimate accurately the contribution of the Fe II multiplet lines to the total intensity of the Hγ–[O III] λ4363 complex from the low-resolution data presented here. However, the data of Evans (1988) indicate that, for the epoch of those observations, the flux due to the Fe II emission underlying the Hγ–[O III] λ4363 region contributed ~25% of the total emission-line flux in the region. If the ratio of the intensity of the emission from Fe II multiplets 27 and 28 to the intensity of the Hγ emission remains approximately constant between the two epochs, then the relative change in the Hγ intensity is ~ × 1.73, which agrees with the monotonic sequence of relative strengths with position in the Balmer series evident from the other Balmer lines.

In addition to the contribution due to the underlying Fe II emission, it is possible that the intensity of the blended [O III] λ4363 emission line has also varied. Since [O III] λ4363 has a relatively high critical density for collisional de-excitation (~2.6×10^7 cm^{-3}), it has been proposed that some fraction of the emission in this line derives from a transition-line region intermediate between the broad- and narrow-line regions (e.g., van Groningen 1984; Crenshaw and Peterson 1986). In NGC 3783, Evans (1988), using a multiple Gaussian decomposition technique, finds evidence from profile comparisons of the [O III] λ4363 and [O III] λλ4959, 5007 emission lines which suggests that up to ~85% of the intensity of the [O III] λ4363 line may be emitted in such a transition-line region with density ~2–3 × 10^7 cm^{-3}. An upper limit to the distance between the transition- and broad-line regions of ~0.15 pc would then be required by the observations so that the [O III] λ4364 line-emitting gas in the transition-line region would have time to react in phase to whatever event resulted in the strong variation of the broad Balmer emission lines.

Besides the Balmer lines, substantial changes in intensity are observed for the broad components of the He I λ5876 and He II λ4686 lines. The intensity of the former derived from the data presented here is ~70% greater than that derived by Evans (1988), although the narrow components of the lines, which are readily distinguished in the data, have similar intensities. The He II λ4686 line evidently shows the greatest change of all the optical broad lines. The intensity of the line derived by Evans (1988) was estimated on the basis of a multicomponent Gaussian fit to the observed part of the profile, since those data do not extend over the entire region of the spectrum covered by the line (a significant fraction of the blue wing was not observed). Because of this, the intensity of the broad He II λ4686 component derived from the 1984 March data is somewhat uncertain. Comparison of the two sets of data indicates that the intensity of the broad He II λ4686 emission was a factor ~4–8 times larger in 1983 May than in 1984 March, where the uncertainty is derived primarily from the unknown correction (for the 1983 May data) for the underlying Fe II emission from multiplets 37 and 38 which contribute a significant fraction of the flux in this region of the spectrum. Large fractional variations in the intensity of He II λ4686 have similarly been observed in NGC 4151 by Antonucci and Cohen (1983), and also in NGC 5548 by Peterson and Ferland (1986), Peterson, Korista, and Cota (1987), and Stirpe, de Bruyn, and van Groningen (1988). The latter authors have also observed similar changes in NGC 3783 at previous epochs, and attribute some part of the variation to the N III λ4640 Bowen fluorescence lines which are strongly coupled to the He II Lyα emission. Eastman and MacAlpine (1985) and Netzer, Elitzur, and Ferland (1985) have investigated the theoretically expected intensities of the Bowen fluorescence lines under conditions appropriate to Seyfert galaxy nuclei, and the latter authors have concluded that the maximum theoretical intensity ratio $I(\text{N III } \lambda 4640)/I(\text{He II } \lambda 4686) \approx 0.4$–$0.85$, depending on density, in these objects. While the resolution is too low to allow a direct measurement of this ratio from the data presented here, an estimate of the contribution may be obtained from the shift of the wavelength centroid of the broad component of the combined feature. Using this technique yields $I(\text{N III } \lambda 4640)/I(\text{He II } \lambda 4686) = 0.45 \pm 0.1$, where the error arises primarily from the uncertainties in the reference positions of the lines because of the correlation between the line centroid blueshift and ionization potential (Pelat, Alloin, and Fosbury 1981; Evans 1988). Comparison of these data with the models of Netzer, Elitzur, and Ferland (1985) indicates that the observed intensity ratio does not exceed the maximum theoretical ratio for gas in the low-density limit, but does not provide sufficient information to further constrain the density of the gas responsible for the N III λ4640 Bowen fluorescence emission, since the efficiency with which these lines are emitted also depends strongly on the shape of the ionizing continuum and the ionization parameter in the emission-line clouds.

None of the forbidden lines observed in the spectra show significant ($> 3\ \sigma$) variations between the two sets of data, with the possible exception of the [Fe X] λ6375, which has an intensity which is apparently a factor of ~2 times *lower* in the 1983 May data when compared to the data taken at the later epoch. Variations in this line on time scales of a few months to a few years have been clearly observed in NGC 5548, and possibly in other Seyfert 1 galaxies also, by Veilleux (1988). In this case, however, one should be cautious in interpreting the difference in the measured line intensities as a real variation, since a substantial contribution to the measured flux in this line in the data of Evans (1988) arises in a weak, broad component which is difficult to measure precisely in the current data because of the limited signal-to-noise ratio. It is important to note that a lower [Fe X] λ6375 flux in the 1983 May data does not necessarily rule out the possibility of enhanced [O III] λ4363 emission from a transition-line region. This is demonstrated by the observations of Evans (1988) which show that the FWHM and blueshift of the line centroid are considerably larger for [Fe X] λ6375 than for [O III] λ4363, suggesting that the dominant contributions to the emission from the two species comes from different volumes of gas. The greater degree of ionization of [Fe X] λ6375 compared with [O III] λ4363, together with an increased critical density for collisional de-excitation (1.2×10^{10} cm^{-3} versus 2.6×10^{7} cm^{-3}), suggest that the [Fe X] λ6375 emission may be more intimately connected with the central ionizing photon source than the [O III] λ4363 emission. If so, then a decrease in the [Fe X] λ6375 emission at the same time as an increase in any [O III] λ4363 emission from the transition-line region may simply result from a varying delay in the response time to changes in the nuclear ionizing continuum.

TABLE 2

Optical Continuum Intensities

Region (Å)	$I_{\text{This Paper}}$[a]	$I_{\text{Evans (1988)}}$[a]
3525–3575.........	4.12 ± 0.13	2.505
3775–3825.........	3.44 ± 0.19	1.938
4000–4050.........	2.64 ± 0.08	1.493
4200–4250.........	2.40 ± 0.07	1.245
5075–5125.........	2.30 ± 0.12	1.192
5550–5650.........	2.42 ± 0.13	1.184
5725–5825.........	2.54 ± 0.18	1.190
6125–6175.........	2.27 ± 0.22	1.139

[a] Units of 10^{-14} ergs cm^{-2} s^{-1} Å^{-1}.

The mean fluxes observed in a series of continuum bands are presented in Table 2, together with the corresponding values derived from the data of Evans (1988). The observed flux level in the continuum was approximately a factor of 2 greater in 1983 May than in 1984 March. However, different spectrograph slit sizes and orientation were used for the two sets of observations, complicating the intercomparison of the nuclear continuum fluxes, since the underlying stellar background emission is spatially resolved and may contribute significantly differing amounts of starlight to the total continuum flux in the two data sets. (The agreement between the relative strengths of the narrow emission lines shows that the region responsible for the emission lines, and presumably also the nuclear nonthermal continuum, is essentially unresolved, so this problem does not exist when comparing the emission-line intensities.) In a similar manner to Evans (1988), one can estimate the contribution of late-type stars to the background-subtracted continuum emission by comparing the equivalent width of the interstellar Na I D doublet in absorption (upper limit ~0.5 Å) with that observed in M32 by Crenshaw and Peterson (1985; ~4.5 Å quoted by Evans 1988). This comparison suggests that the contribution by the late stellar population to the background-subtracted data does not exceed ~10%. If this

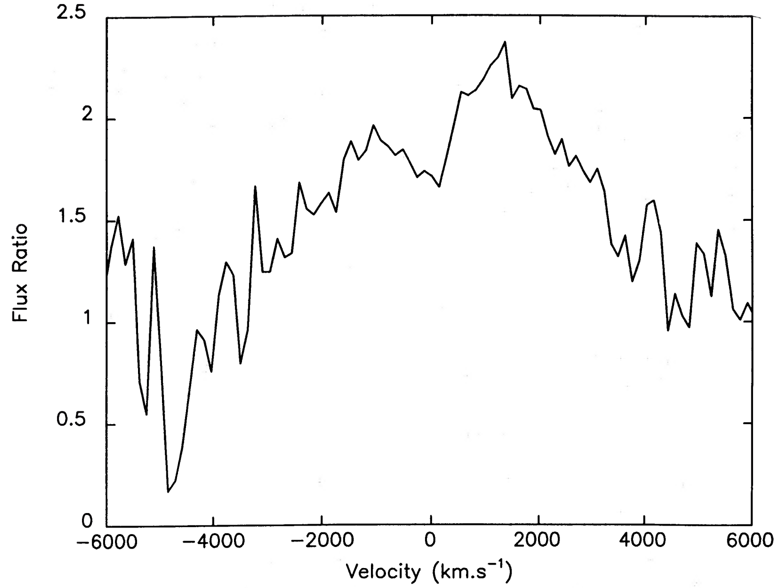

FIG. 2.—Result of dividing the line profile derived from the present data by the profile derived from the data of Evans (1988) for Hβ. The background continuum level and narrow forbidden-line contamination were subtracted from each spectrum and the spectra smoothed to the same resolution prior to the division.

contribution is representative of the fraction of the background-subtracted continuum emission which is due to the stellar and (nonnuclear) galaxian components, then it is possible to conclude that the nuclear continuum flux decreased over the same period as the broad lines. There is no evidence in the data for a significant change in continuum slope between the two epochs.

The mean 5550–5650 Å nuclear continuum flux derived from the literature (Atwood, Baldwin, and Carswell 1982; Ward and Morris 1984; Morris and Ward 1988) for the period 1981 April until 1984 June is $1.2 \pm 0.2 \times 10^{-14}$ ergs cm^{-2} s^{-1} Å^{-1}, which is in excellent agreement with the value measured from the 1984 March data, but a factor of 2 lower than in 1983 May. Over the same period the observed Hβ/[O III] λ4959 ratio has varied from a minimum of ~2.8 (Atwood, Baldwin, and Carswell 1982) to a maximum of ~3.8 (Morris and Ward 1988), with the exceptions of 1983 May (this paper), and 1982 January when Hβ/[O III] λ4959 ≈ 5.3 (Ward and Morris 1984). One plausible explanation for these data is that nuclear continuum source in NGC 3783 spends much of its time in a relatively quiescent phase, with the continuum flaring occasionally, perhaps in response to an accretion event such as that seen in NGC 5548 (Peterson and Ferland 1986; also see below). The broad-line emission would then be enhanced because of the increased continuum flux, but would fade more slowly than the nuclear continuum because of geometrical and time delay effects. If such an hypothesis is correct, the 1983 May data would correspond to a time near or shortly after the maximum continuum luminosity, while the 1982 January observations of Ward and Morris (1984) would correspond to a period somewhat later after a flare when the continuum had settled back down to its quiescent state.

The spectral resolution and signal-to-noise ratio of the data presented here are too low to allow detailed studies of the variations of the intrinsic profiles of the broad lines to be carried out, although the gross differences between the profiles of the strongest Balmer lines are visible in Figures 2 (Hβ) and 3 (Hα). These figures were obtained by dividing each line profile derived from the 1983 May data by the profile derived from the 1984 March data, after smoothing the latter to the resolution of the current data. Before computing the profile ratio, a smooth continuum level and any contaminating narrow forbidden lines were first subtracted off. The intensities of the latter were assumed to remain constant at the level measured by Evans (1988), but were smoothed to the same resolution as the earlier data by convolving their previously measured profiles with a Gaussian of the appropriate width.

Figure 2 demonstrates that the intensity of the Hβ emission was considerably greater at the epoch of the current data (1983 May), compared to the 1984 March data, within $|V| \lesssim 4000$ km s^{-1} of the line center. A small dip in this trend with a width ~1100 km s^{-1} centered on the line is visible both in the Hβ profile (Fig. 2) and also the Hα profile (Fig. 3). This dip occurs because of the presence of a narrow component to the Balmer lines which was not subtracted prior to the profile divisions, and which presumably does not vary with the broad component(s) of the lines. The intensity of the red side of the Hβ profile ratio with $V \lesssim 3000$ km s^{-1} is approximately 30% greater than the corresponding region on the blue side of the line, indicating that the profile was more red asymmetric in 1983 May than in 1984 March. It is interesting to note, however, that a corresponding change in the red side of the Hα profile is not apparent in Figure 3, implying that emission from multiple components with different Balmer decrements must contribute to the overall line profiles. Similar variations of the Balmer line profiles have been observed in NGC 5548 by Stirpe, de Bruyn, and van Groningen (1988), who concluded that the structure in the profile ratios may be due to a combination of (*a*) differing physical responses of individual broad-line clouds to changes in the ionizing continuum source, presumably because variations in the physical conditions (e.g., density, ionization structure) in the clouds, and (*b*) variable responses of the broad-line clouds due to geometrical and time-delay effects as the effect of the continuum variations propagates through the broad-line region's velocity structure.

A further interesting feature of the Hα profile ratio is the level of the profile ratio for $|V| \gtrsim 2500$ km s^{-1}. Figure 3 shows that the intensity of Hα has apparently *decreased* in this region

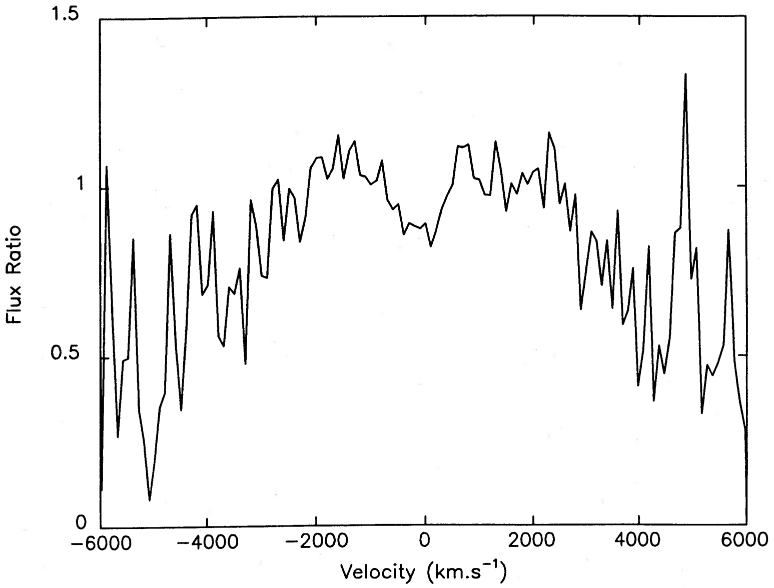

FIG. 3.—As Fig. 2, except for Hα

whereas the other Balmer lines have increased. Inspection of the same region of Figure 1 shows evidence for a broad minimum in the level of the *difference* spectrum when compared the level blueward of ~6340 Å. The decrease cannot be the result of an error in the normalization of the flux scale in the data set of Evans (1988), since the spectral region encompassing Hα was contiguous redward of ~6245 Å. Both the location and FWHM (~11,000 ± 2000 km s^{-1}) of the minimum suggest that a variation of the intensity of the very broad (~10,100 km s^{-1} FWHM) component of Hα (Evans 1988) between the two epochs may be responsible for this feature in the difference spectrum. This interpretation is also suggested by the fact that Hα appears to be superposed on a base which is marginally more convex in the Evans (1988) data than in the current data. If the very broad component of Hα is produced in a part of the broad-line region which is very closely associated with the nuclear continuum source, this may represent the response of that gas to a drop in the continuum level as the effect of the latter propagates through the velocity structure of the broad-line region. In particular, it is possible that this may mark the commencement of the drop in continuum intensity which propagated throughout the broad-line region and which produced the state of considerably lower nuclear activity observed in the later data of Evans (1988), while the increase in the very broad component apparent in the later data may mark the onset of a new period of increased nuclear activity.

Variations in the broad Balmer-line profiles of NGC 3783 may be traced back in the literature for at least 10 yr. Unfortunately, many of the data sets have low spectral resolution or signal-to-noise ratio, or do not have absolute flux calibrations, limiting their usefulness to some extent. Nevertheless, it is possible to at least qualitatively study the overall changes in the broad Balmer-line profiles which have taken place during the past decade. The high resolution data presented by Pelat, Alloin, and Fosbury (1981) for the epoch 1977.0 represent a good starting point. These data were compared in detail with the data of Evans (1988) in the latter paper, and that comparison will not be repeated here. Suffice it to say here that at that epoch the broad Balmer lines had a strong and noticeably convex (particularly Hβ) red asymmetric profile with a concave blue wing. By epoch 1981.3 (Ward and Morris 1984) there was still a distinct red asymmetry, but the concavity of the blue wing had essentially disappeared. A little over a year later (epoch 1982.5; Menzies and Feast 1983) the broad profile was almost triangular with only a small amount of red asymmetry. Comparing their data to that of Pelat, Alloin, and Fosbury (1981), Menzies and Feast (1983) concluded that the change in the broad Balmer-line profile that took place between 1977 and 1982 could be well approximated by the addition of a new approximately Gaussian line component with a FWHM of ~1370 km s^{-1} and a centroid blueshift of ~1630 km s^{-1} relative to the systemic velocity, together with a simultaneous decrease in Pelat, Alloin, and Fosbury's (1981) component 3 (FWHM ≈ 1170 km s^{-1}, centroid blueshift ≈ 445 km s^{-1}). The additional blue component had disappeared by epoch 1983.4 (this paper), leaving a slightly red asymmetric profile with concave wings. Ten months later (epoch 1984.2; Evans 1988) the profile was almost unchanged (although the total intensity of the broad Balmer lines had varied enormously), except for a small decrease in the red asymmetry. At this point in time the profile was almost symmetrical. By epoch 1986.4 (Stirpe, de Bruyn, and van Groningen 1988) the blue wing had developed a small but noticeable asymmetry which remained virtually unchanged through epoch 1987.0.

Clearly the behavior exhibited by the Broad Balmer lines over periods of a few years is exceedingly complex, with the line profiles varying as the contributions from different volumes of the broad-line gas change, either because of variations in the shape and intensity of the ionizing continuum, changes in the physical conditions in the broad-line clouds, bulk mass motions in the broad-line region, or any combination of these factors. Quite evident is the fact that further monitoring of the Balmer-line profiles in such objects over time scales of a few months to a few years is clearly necessary to further our understanding of them. It is also evident that such monitoring should have sufficiently high spectral resolution and signal-to-noise ratio that the *individual* Balmer lines (at least Hα and Hβ) can be separately studied and compared, and that absolute line and continuum fluxes are required to determine whether the line profile changes are correlated with continuum variations.

Comparison of the observational results with the theoretical Seyfert and quasar broad-line region photoionization models of Kwan (1984) indicates that the qualitative predictions of those models are, in general, consistent with the data. For example, the models predict that Balmer lines higher in the series are more sensitive than Balmer lines lower in the series to continuum variations and this indeed agrees with the observed behavior. Similarly, the theoretical models predict the observed strong dependence of the intensity of He I λ5876 on the incident continuum flux level.

A more detailed comparison of the model predictions and the observations for the two epochs, however, indicates some inconsistencies if one attempts to explain the observations solely through a change in the ionizing continuum flux intensity. Kwan's (1984) photoionization models predict that the decrease in the broad Hβ/Hα ratio between 1983 May and 1984 March corresponds to a decrease of about a factor of ~10–15 in $N_0 \Gamma^i$ (effectively the incident ionizing continuum flux on a cloud; N_0 is the cloud nucleon density at the illuminated face, and Γ^i is the ionization parameter) between the two epochs. In contrast, the absolute Hβ flux decreased by no more than a factor of 2, suggesting (according to the models) that $N_0 \Gamma^i$ similarly decreased by about a factor of 2. The intensity of broad He I λ5876/Hβ did not vary significantly between the two epochs, indicating that either $N_0 \Gamma^i$ remained approximately constant, or that $N_0 \Gamma^i \lesssim 2 \times 10^8$ cm^{-3}.

One possible explanation for the observational data within the framework of Kwan's (1984) models would be to invoke an order of magnitude decrease in $N_0 \Gamma^i$ between 1983 May and 1984 March (subject to the constraint that $N_0 \Gamma^i \lesssim 2 \times 10^8$ cm^{-3} from the He I λ5876/Hβ ratio data) to account for the observed change in the Balmer decrement, together with a large (at least a factor of 10) increase in τ_L, the Lyman edge optical depth in the emitting clouds. The effect of increasing τ_L is to reduce the dependence of the absolute Hβ flux on the incident ionizing continuum flux to account for the relatively small observed drop in the Hβ flux between the two epochs.

A similar scenario to this was suggested by Peterson and Ferland (1986) to explain a probable accretion event on NGC 5548 which resulted in a large increase in the observed He II λ4686 emission (approximately a factor of 10; for comparison the broad He II λ4686 emission in NGC 3783 varied by a factor of 4–8) associated with relatively moderate increases in the optical continuum and Balmer-line intensities. Kallman and Elitzur (1988) have recently computed new models to attempt to explain the event observed by Peterson and Ferland (1986) in NGC 5548. They concluded that while such a scenario is feasible, the very low radiative efficiency of the emission line clouds with low τ_L (and hence low column density) requires a source covering factor of approximately unity during the luminous phase. Evidence from UV spectra suggests that in many quasars the covering factor is ~0.1, although this result is inversely correlated with luminosity, so that Seyfert galaxies have somewhat higher covering factors (Kinney *et al.* 1985).

As alternatives, Kallman and Elitzur (1988) propose two additional scenarios to describe the NGC 5548 data. The first of these requires a large increase in the cloud ionization parameter (which is initially very low) during the luminous phase, either because of a change in cloud pressure or position or a change in ionizing flux, while the cloud column density remains constant. The disadvantage of this scenario in the case of NGC 3783 is that the increase in ionization parameter required to flatten the Balmer decrement would also increase the absolute Hβ flux beyond what was observed during the luminous phase unless the source covering factor is decreased below the standard value. To match the observed variations of both the Balmer decrement and the Hβ flux it seems likely that this would require an unreasonably low value for the source covering factor (Kallman 1988). The second alternate scenario invokes a change in the shape of the ionizing spectral distribution during the luminous phase through an EUV flare. This scenario has the advantage that it does not require any changes to the intrinsic properties of the broad-line clouds to explain the observed spectral variability, but for NGC 3783 it suffers from the disadvantage that it cannot explain the observed change in the Balmer decrement.

IV. CONCLUSIONS

Comparison of new intermediate-resolution optical spectrophotometry of the nucleus of the southern Seyfert 1 galaxy NGC 3783 with data obtained by Evans (1988) approximately 10 months later indicates that the broad emission lines have varied substantially in intensity over this period. Both the broad Balmer lines and the He I λ5876 and He II λ4686 recombination lines have varied between the two epochs. In addition, the level (but not the slope) of the background-subtracted continuum has also varied between the two sets of observations, with an increased continuum intensity level associated with increased broad-line emission. Over the same period the intensities of both the narrow forbidden lines and the narrow-line components of He I λ5876 and He II λ4686 have not varied, and comparison with previously published data indicates that the time scale for variations of the narrow fobidden lines is at least 10 yr.

The data with the stronger broad Balmer-line emission have an overall flatter Balmer decrement than the data for which the line emission is weaker, although the profiles of the Hα and Hβ lines have varied independently of each other, suggesting that there are contributions from several line components with different intrinsic Balmer decrements. Comparison of the relative fractional changes of the contributor to the Hγ–[O III] λ4363 blend, probably emission from Fe II multiplets 27 and 28, has varied together with the broad Hγ emission between the two epochs.

Comparison of the data with the quasar and Seyfert broad emission-line cloud photoionization models of Kwan (1984) and Kallman and Elitzur (1988) suggests that the observed variability may be best explained by a model in which both the incident ionizing flux on the clouds and the cloud optical depth varied, but does not seem to be compatible with models in which only ionizing flux level or spectral shape change. These models indicate that a low column density and large source covering factor may be required for the clouds responsible for the observed luminous phase.

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