

LINE VARIATIONS IN QUASARS AND SEYFERT GALAXIES

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ABSTRACT

We present quantitative estimates of the sizes of broad-line regions (BLRs) in three well-studied Seyfert I galaxies and discuss how these differ from previously reported size estimates for NGC 4151. We analyze both Lick Observatory and *IUE* satellite data on NGC 4151 and show that both are consistent with the high-ionization filaments (those emitting C IV, He II, and the high-order Balmer lines) mostly lying ~ 5 lt-day from the central source. The low-ionization filaments are 3 or 4 times further out. The Ohio State data on Akn 120 show the $H\beta$ emitting region to be ~ 6 lt-day from the central source, and *IUE* data suggest that the Ly α region in Mrk 509 is ~ 10 lt-day out. Our results imply that the densities in broad-line regions are a couple of orders of magnitude higher than in current standard models. For the objects studied here, the light crossing times are of the same order of magnitude as the continuum variability time scales, so kinematic mapping of the broad-line regions will be extremely difficult.

Subject headings: galaxies: Seyfert — line profiles — quasars

I. INTRODUCTION

The broad emission lines in quasar-like objects arise from photoionization by a continuum extending to ultraviolet and X-ray energies. This continuum has long been known to vary in the optical region (Smith and Hoffleit 1963; Sharov and Efremov 1963) and in the X-ray region (Davison *et al.* 1975). Obviously if the photoionizing continuum varies, the emission-line spectrum must change as well. Bahcall, Kozlovsky, and Salpeter (1972) pointed out that these variations could be helpful in exploring the structure of the emission-line regions. Andrillat and Souffrin (1968) showed that the broad emission lines of Seyfert galaxies do indeed undergo drastic changes. Probably all Seyfert I galaxies show line variability (Peterson, Crenshaw, and Meyers 1985, Chapman, Geller, and Huchra 1985). The first systematic observational study of emission-line variability was by Cherepashchuk and Lyutyi (1973; see also Lyutyi 1977), who estimated that changes in the H α emission line were delayed by a few weeks relative to changes in the continuum in a number of Seyfert galaxies.

In this paper we begin by pointing out some of the pitfalls in using line variability to study the structure of emission-line regions. We discuss the response of a *realistic* broad-line region (BLR) cloud to changes in the incident continuum and show that different lines may respond very differently, although they arise in the same physical regions (this important effect was neglected in a recent interpretation by Ulrich *et al.* 1984; see Ulrich *et al.* 1986). We illustrate how rise times cannot be used to deduce emission-line region sizes. We then do cross-correlation analyses of published optical and ultraviolet data for NGC 4151, Akn 120, and Mrk 509 and discuss the implications of our results for models of Seyfert galaxies.

II. GENERAL THEORETICAL CONSIDERATIONS

a) Nature of Continuum Variability

Before addressing the problem of how emission lines respond to changes in the continuum flux, we need to consider

two questions. First, on what time scale does the continuum vary? Second, does the shape (spectral energy distribution) stay the same? Until recently, most measurements of the continuum flux have been made in the optical, while the emission lines respond primarily to wavelengths below the Lyman limit. This short-wavelength radiation has never been monitored along with changes in line intensity.

Continuum variations in a Seyfert galaxy were first discovered in NGC 4151 (Fitch, Pacholczyk, and Weymann 1967). This remains the best-studied case, and its behavior appears to be typical of Seyfert galaxies in general (Lyutyi 1977). The nature of the variability is far from completely understood. Variability is present on time scales ranging from days (sudden “flares” or “dropouts”) to decades. In NGC 4151 the slower variations often appear to be quasi-periodic with periods ranging from 3 months to 16 yr (see Lyutyi and Otcyanskii 1982), but a careful power-spectrum analysis by Pacholczyk *et al.* (1983) reveals no *true* periods.

Lyutyi (1977) has shown that the short-period flares in Seyfert galaxies all have the same rise time (~ 1 week) and the same relative amplitude ($\Delta U \approx 0.5$ mag). Dibai and Lyutyi (1976, 1984) find the rise time (Δt) of flares to be proportional to the luminosity of the quasar to the 0.3 power, but to be fairly constant in a given quasar regardless of the amplitude of the flare. Interestingly, the rise time seems to be independent of both the absolute magnitude of the Seyfert and the luminosity of the flare. The flares decay over 3 times longer than the rise time. Although most of the photometric monitoring has been in the optical wave band, at least one flare has been seen in the ultraviolet with *IUE*; notably the 1979 May 3–25 event in NGC 4151 (Ulrich *et al.* 1984).

NGC 4151 also shows some rapid flares in the X-ray, but the rise times are much faster; days, not weeks (Lawrence 1980). It is not clear that the optical and X-ray variability are correlated (Bassani 1982; Perola *et al.* 1983), and there is no information on how the spectral shape changes between the X-ray and optical regions.

Both ground-based optical observations (e.g., de Bruyn 1980; Oke, Readhead, and Sargent 1981; Yee and Oke 1982) and satellite ultraviolet spectrophotometry (Barr *et al.* 1983; Perola *et al.* 1983) show that Seyfert galaxies are more variable at short wavelengths than at longer ones. We would like, however, to draw attention to an ambiguity in interpreting these changes in spectral shape, which is not always appreciated: if the spectrum becomes flatter as the continuum brightens, this can be due *either* (i) to the flux increasing more rapidly at shorter wavelengths, *or* (ii) to the spectrum consisting of two discrete components, a "flat" and a "steep" one, and one of these components being more highly variable than the other. Different authors have offered different interpretations: some favor multiple components; others prefer a single component of varying spectral shape. These models cannot be distinguished with present observational data.

Since there is abundant observational evidence that the optical and extreme ultraviolet continuum vary to some extent in step, we assume in the remainder of this work that the ionization parameter U_1 (the ratio of ionizing photon density to gas density) is proportional to some power of the optical flux F_{opt} :

$$U_1 = F_{\text{opt}}^k.$$

The fact that variability is greater at shorter wavelengths suggests $k > 1$.

An additional complication that should be mentioned is the possibility that the continuum variability we see is different from what the broad-line region clouds see because a component of the continuum is relativistically beamed toward the observer. Blandford and Rees (1977) have proposed that this is the case for BL Lac objects, and Scheuer and Readhead (1979) have extended this idea to flat radio spectrum quasars. For most active nuclei, however, the contribution of any beamed radiation to the optical and UV continua is probably slight (see Gaskell 1982a; Moore and Stockman 1984). Lloyd (1984) concludes from a study of optical variability that neither the quiescent optical luminosity of quasars nor the optical outbursts have significant beamed contributions. The significant line flux changes that *have* been seen in objects with variable optical continua (e.g., those analyzed below) suggest that the flux seen by the BLR is the similar to that seen by us (Gaskell 1982a).

b) Response of a Single Broad-Line Cloud

Let us consider the response of a single "typical" broad-line region cloud to changes in the ionizing flux. There has been considerable effort (and fair success) in the last decade in explaining the observed intensity ratios in Seyfert galaxies and quasars by such "typical" clouds. Our results in § III will suggest that such simple models do not represent what actually occurs, but the current standard models do give many insights. In these models, although the details of the EUV continuum of Seyfert galaxies are very uncertain, the emergent line spectrum is fairly insensitive to these details as long as there is still significant flux at X-ray energies. The main quantity determining the line ratios is just the ionization parameter U_1 (see Davidson 1977, and references therein).

We begin by considering the relevant time scales for a change in the ionization conditions in a BLR cloud, when the photoionizing flux changes. Ferland and Mushotzky (1982) have calculated photoionization models for the broad-line clouds under conditions expected in NGC 4151. Assuming an

electron density $n_e = 10^9 \text{ cm}^{-3}$, a typical cloud is 10^{12-13} cm thick (and perhaps much wider; Mathews 1982a). The photon diffusion time scale for even an optically thick line such as Mg II ($\tau \approx 10^6$) is negligibly small, as is the recombination time. The sound crossing time is much longer, $\sim 10^6-10^7 \text{ s}$ (i.e., of the order of 1 month); this is longer than the rise time of most Seyfert flares. Thus a cloud probability cannot change its density as fast as the ionization changes; the ionization parameter is thus linearly proportional to the ionizing continuum flux.

Slower changes in the photoionizing flux could lead to more spectacular effects. A gradual increase in continuum intensity will initially raise the ionization parameter U_1 , but the temperature and hence the pressure will also rise. The cloud thus tends to expand, lowering the density and further increasing the ionization. When the ionization is fairly high (as in most Seyfert galaxies) this process can run away, and the cloud may evaporate in a few sound-crossing times. But this will not happen in the short-term flares observed in Seyfert galaxies.

Previous efforts to infer the size and structure of the broad-line region from variability studies have assumed that the line flux increases linearly with the incident continuum; Blandford and McKee (1982) have developed a comprehensive theory for this case (see also Capriotti, Foltz, and Peterson 1982; Antokhin and Bochkarev 1984). We want to point out that this condition is not usually even approximately satisfied, even if the ionization parameter U_1 were linear with the observed flux. The behavior of the line fluxes of C IV $\lambda 1549$, C III] $\lambda 1909$, and Mg II $\lambda 2798$ with varying ionization parameter is well known. Convenient plots can be seen in Mushotzky and Ferland (1984), who show that the line ratios of most Seyfert spectra are best fitted by $\log U_1 = -2.5$ to -1.5 .

We particularly wish to emphasize the different relations of the fluxes in C III], C IV, and Mg II to the continuum flux. C IV $\lambda 1549$ increases more rapidly than linearly with U_1 , over almost the entire range of interest. C III] $\lambda 1909$ and Mg II $\lambda 2798$, on the other hand, hardly increase at all. Failure to realize this important difference has led to erroneous deductions about the structure of the emission-line region in NGC 4151.

c) Response of an Entire Broad-Line Region

The distribution of emitting clouds within the BLR is not well understood, but since the line shapes are roughly symmetric, it is quite plausible that the clouds are placed isotropically around the nucleus (e.g., Mathews 1982b). Here we discuss only the case where line-emitting material lies in spherically symmetric shells about the central source. First, we give a simple derivation of the line responses in the case where emission from any cloud is linearly proportional to the incident continuum flux; these are all known results. Then we show how the responses are changed in the realistic case where that proportionality no longer holds.

Consider a shell of gas, with radius r_s , around a continuum source O, observed at a distance $D \gg r_s$ from a point E. At time $t = 0$, the source O sends out a light pulse, of luminosity $L\delta(t)$, which ionizes the gas, causing it to emit line radiation. The unobscured continuum light is received at E at a time $T = D/c$; line radiation continues to arrive for some time afterward. Recombination times in the clouds are short so that line radiation is effectively emitted as soon as the continuum light falls on the cloud; the locus of the gas from which line emission is observed at any time can be found. The line radiation reaching

E at time $t + T$ has followed a path made up of two sections: (i) from the source at O to the gas, and (ii) from the gas to the observer at E. The total path length must sum to $c(t + T)$. This defines an ellipse with foci at O and E; when $D \gg r_s$, the ellipse degenerates into a parabola of semilatus rectum $ct/2$, with its focus at O and axis along OE. In polar coordinates (r, θ) with origin at O and $\theta = 0$ along the line OE, the lit up gas lies on

$$r_s(1 + \cos \theta) = ct. \quad (1)$$

In an interval dt , a solid angle $d\Omega$ of the shell is lit up, where $d\Omega = 2\pi \sin \theta d\theta = 2\pi cdt/r_s$; this is independent of time for $0 < t < 2r_s/c$. During this time, a quantity $Ld\Omega/4\pi = cLdt/2r_s$ of continuum light has fallen onto the shell. Suppose for the moment that the line emission F_l is linearly related to the continuum intensity, and that each cloud radiates its line emission isotropically. Then the line emission received at time t after the continuum outburst is seen is given by

$$F = \frac{cL}{2r_s} \epsilon \quad \text{for } 0 < t < \frac{2r_s}{c} \\ = 0 \quad \text{otherwise} \quad (2)$$

where ϵ is a reprocessing coefficient. The line flux is constant over the interval $0 < t < 2r_s/c$; this result has been known for some time (Couderc 1939; see also Morrison and Sartori 1969).

Adding up the line flux from many shells of material shows that, after a brief outburst of ionizing radiation in the center of any spherically symmetric cloud of material, the maximum line flux is seen at the same time as the continuum brightening; this was pointed out by Bahcall, Kozlovsky, and Salpeter (1972). Thus the time at which the emission lines are brightest, and the time taken for them to reach their peak intensity, does not necessarily give any information at all on the size of the emission-line region.

The time centroid of the line emission is delayed relative to the continuum flash by a time of r_s/c , the light-travel time across the broad-line region. Since the response to any pattern of continuum illumination can be found by adding up responses of the form (2), this delay is about the same for any continuum outburst. A correlation analysis such as we perform in § III should give reliable values for the sizes of broad-line regions if the data are adequate.

We have assumed that the line-emitting clouds reradiate their energy isotropically. If the line flux is directed predominantly back toward the continuum source, then the line brightness may be observed to peak later than the continuum; this can be seen from Figure 2 of Blandford and McKee (1982), showing their model "RAN." However, the line brightness reaches nearly its peak value at $t = 0$, unless the anisotropy is extremely high—and this is difficult to reconcile with the symmetry of the line profiles (Osterbrock and Shuder, 1982). Similarly, if the clouds are not distributed spherically, the line emission may be delayed. Again, only a substantial departure from a spherical distribution will introduce a large delay.

In the linear theory, the amplitude with which line emission varies is inversely proportional to the radius of the broad-line region. Lines which arise closest to the continuum source show the largest amplitude of variation. Unfortunately, this property cannot usefully be employed to measure distances in the broad-line region because it does not persist when the line flux is no longer simply proportional to the continuum flux.

Suppose that the line flux from an individual cloud is proportional to the β power of the ionizing flux incident on it.

Then formula (2) for the observed line emission becomes

$$F_l = \epsilon(cL/2r_s)^\beta \quad 0 < t < 2r_s/c \\ = 0 \quad \text{otherwise} \quad (3)$$

The duration of line emission is not affected, but its intensity changes. If the continuum does not rise instantaneously but follows a pattern $L_c = L_c(t)$, then the line response is the sum of responses to radiation emitted at any particular time:

$$F_l(t) = \epsilon(c/2r_s)^\beta \int_0^{2r_s/c} L_c^\beta(t-x) dx.$$

Figure 1 shows the line response for two cases of continuum variability: (i) L_c rises from unit level to a Gaussian peak of height 2, and then falls; (ii) L_c doubles by a linear rise to a new steady state. As the line becomes more responsive to the continuum level (as β rises), the line variation increase in amplitude. The time centroid of emission is unaffected, as is the time required for the line flux to rise and fall to its original level after a finite continuum outburst. But the time taken for the line flux to increase by a factor of 2 is exactly $1/\beta$ times the two-folding time of an exponentially rising continuum. If $\beta > 1$ (the line responds more strongly than linearly to the continuum flux), then the line flux may actually vary with a larger amplitude than the continuum. Thus measures of the rise time as used by Ulrich *et al.* (1984) can only be used to infer the relative radii of different parts of the broad-line emitting region if the lines in question respond in the same way to continuum changes. From Figure 1 of Mushotzky and Ferland (1984), we deduce that for Mg II, $\beta \approx 0.5$; for C IV, $\beta \approx (1.8-0.5)$, and for C III], $\beta \approx 0.6$, so we expect that the two-folding times for Mg II and C III] will be about twice the time for C IV, if all these lines are formed in the same region (and the ionization parameter U_1 has the high value suggested by Mushotzky and Ferland).

This problem with the original argument of Ulrich *et al.* (1984) has also been pointed out independently by Carroll (1985), who shows that the rise times observed in NGC 4151 do not require a stratification of the emission-line region (see also Ulrich *et al.* 1986). Nonetheless, when we perform the cross-correlation analyses of Seyfert galaxy line and continuum data (§ III below), we show that there is indeed a stratification into at least two regions in at least NGC 4151 and probably in all quasar-like objects. The sizes of these regions are, however, significantly smaller than those claimed by Ulrich *et al.* (1984). We will also argue that C III] $\lambda 1909$ is not the main contributor to the $\lambda 1908$ blend.

The correct way to deduce size information from line and continuum flux measurements is to *cross-correlate* the measurements (this is essentially what was done by Cherepashchuk and Lyutyi 1973). For a single-shell model of the BLR, it can be seen from Figure 1 that this gives the light crossing time (r_s/c) for all values of the parameter β . Notice that this will give the BLR size even when the time scale for continuum variation is much greater than the light crossing time. In this latter case the *time taken* for the line flux to change is merely an indication of the continuum variation time scale. If the BLR does not consist simply of a shell but is extended in radius, then the line emission from material closest to the central source will respond most quickly and with the largest amplitude to continuum fluctuations. Thus the peak in the line-continuum cross-correlation function will indicate a light-travel time typical of the inner parts of the line emitting region. In the following section we analyze some of the data available for three Seyfert galaxies.

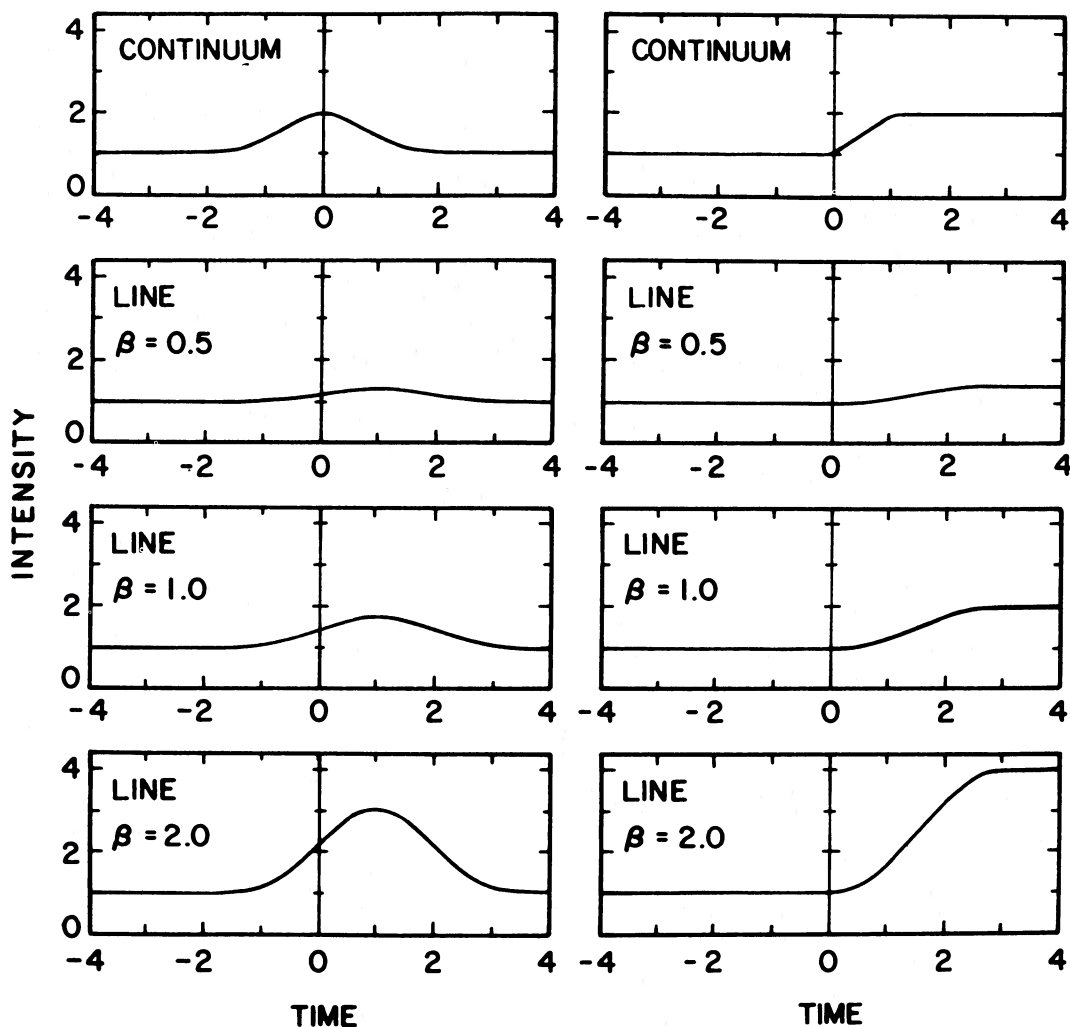


FIG. 1.—Responses of the total line flux from spherical ensembles of clouds to two examples of varying ionizing continuum flux. Time is in units of the light crossing time (r/c).

III. THE SIZES OF SEYFERT BROAD-LINE REGIONS

a) Method and Errors

For the three Seyfert galaxies considered below we have taken data from the indicated published sources and in some cases rejected questionable data points. To perform the cross-correlations we have interpolated linearly between continuum measurements and then extended the continuum measurements backward and forward in time at a constant level equal to the first and last values, respectively (to minimize the introduction of spurious features into the cross-correlation; apodizing is inappropriate for the rather small series of observations currently available). Assessment of the errors in the positions of the peaks is difficult because the data are irregularly sampled. We made limited experiments to estimate the significance of our results. The Ohio State Akn 120 data are sufficiently plentiful that we could analyze two observing seasons separately. For other data sets we note the effects of removing extreme values. Simulations made by scrambling the data values but keeping the same sampling suggested that a correlation of 0.3 in a 50 day wide range of lags would be achieved by chance 10% of the time. This is probably an underestimate of the errors because the line variations are not

random (for example, adjacent days or nights usually give very similar results). Taking synthetic line data resembling the line data gives a probability of 25% of getting a correlation of 0.4 in a 50 day interval, but this is probably an overestimate of the errors since we believe that the similarities in structure between the line and continuum light curves are a result of them being closely correlated. The consistency of our results below supports this belief.

One possible systematic error that would produce a spurious peak in the correlation near zero days lag is a correlation between errors in the line strengths and the continuum fluxes. This is most likely in the Lick and Ohio State data sets, where both the line strengths and continuum fluxes are normalized to [O III] $\lambda 5007$. The uncertainties in the technique have been considered theoretically by Peterson and Collins (1983). Our simulations showed that correlated errors of 5% (0.05 mag)—about the accuracy claimed by the authors—would create an artificial peak in the correlation function at zero lag of amplitude 0.15 (not enough to explain the peaks we will find below but enough to distort them slightly). Inspection of observations taken very close together, however, reveals no indication whatsoever of the errors being correlated, so we do not believe that there is any artificial excess correlation around zero days lag.

b) *Akn 120*

The $H\beta$ and $\lambda 5000$ continuum measurements of Peterson *et al.* (1983, 1985) for Akn 120 form the largest body of data on variability in any one emission line. These data come primarily from spectra taken with the IDS on the Perkins 1.8 m reflector supplemented by a few spectra obtained with the intensified Reticon system on the Steward 90 inch (2.25 m) and the MMT. Peterson *et al.* (1985) find no systematic differences between measurements based on spectra from different telescopes. In Figure 2 we show that there is strong clear peak in the correlation function at a delay of 6 days. The strength and position of the peak are essentially unchanged when the data are divided into two halves (essentially two observing seasons), and these halves are considered separately (the peak occurs at 5 and 8 days, respectively).

c) *NGC 4151*

NGC 4151 has been the subject of three major studies (Cherepashchuk and Lyutyi 1973; Antonucci and Cohen 1983; Ulrich *et al.* 1984). Cherepashchuk and Lyutyi measured $H\alpha$ $\lambda 6563$ with a tunable interference filter and measured the continuum flux with broad-band (U , B , V) filters. Antonucci and Cohen did spectrophotometry with the IDS on the Lick Observatory 40". They supplemented these spectra with a few taken with the IDS on the Lick 120" by other observers.

Antonucci and Cohen report line measurements for $H\gamma$, $H\beta$, $H\alpha$, and $He II \lambda 4686$, and continuum measurements corrected for galaxy contamination. For some nights they present both small and large aperture observations; on the basis of a comparison of these we have increased all small aperture $[O III]$ line strengths by 8%. The Ulrich *et al.* (1984) observations were made with the *IUE* satellite; we have omitted the two observations for which the calibration was considered uncertain.

We consider below the correlations found for each line.

i) $H\alpha$ $\lambda 6563$

Not all the Russian $H\alpha$ measurements have been published. We obtained those that have been from Lyutyi and Cherepashchuk (1972) and measured the remainder from Figure 1 of Lyutyi (1977). All the relevant U continuum data are published in Lyutyi (1977). When we cross-correlated the data as described above, the peak we found in the correlation function (not shown) was only 0.19, which we do not consider sufficiently strong to determine the size of the $H\alpha$ emitting region reliably. We would not exclude any lag between 0 and 30 days (the value claimed by Cherepashchuk and Lyutyi). The problem is not with the accuracy of the Russian $H\alpha$ measurements (which is 0.02 mag rms and hence better than the IDS measurements) but with the rather small amplitude of the $H\alpha$ variability (0.06 mag rms) in the years they monitored NGC 4151. This is a pity

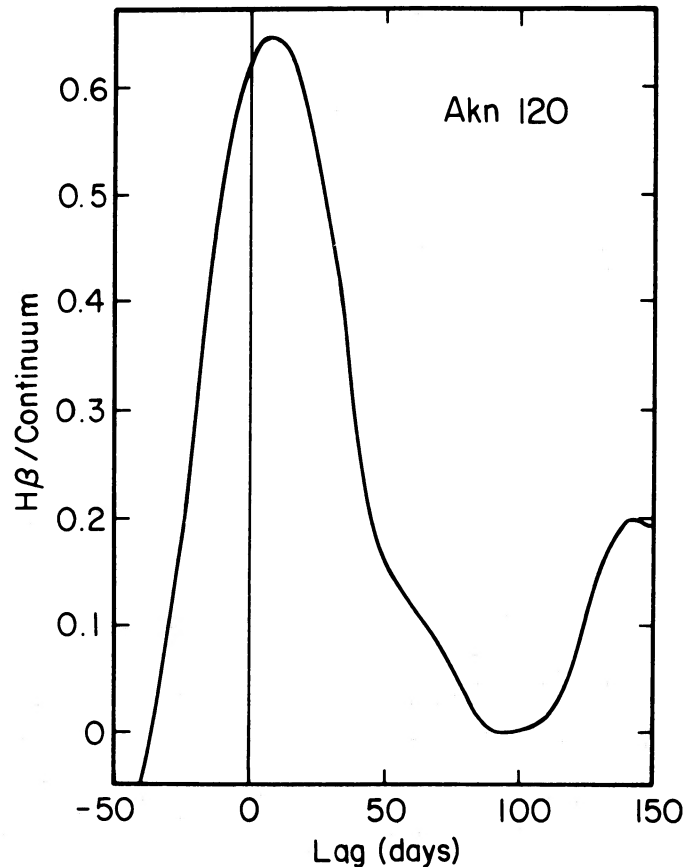


FIG. 2.—Correlation between the Ohio State measurements of $H\beta$ $\lambda 4861$ in Akn 120 and the total continuum flux (quasar and galaxy continuum) at 5000 \AA (rest frame), as a function of the lag between the line and continuum measurements.

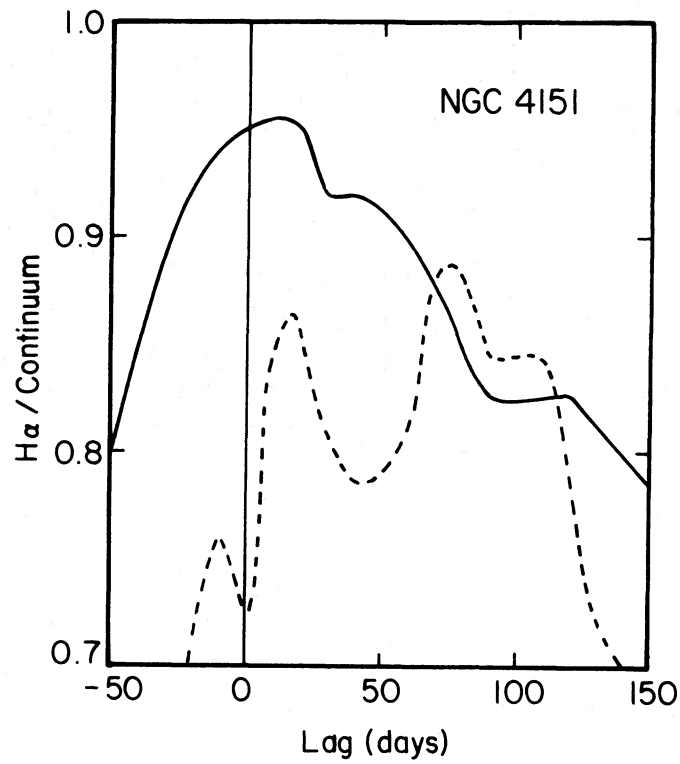


FIG. 3.—Correlation between $H\alpha$ $\lambda 6563$ in NGC 4151 and the galaxy-subtracted continuum at 5000 \AA , vs. the lag between the line and continuum measurements. Dashed curve is for all the Lick data; solid curve is obtained when the most deviant point is removed (see text).

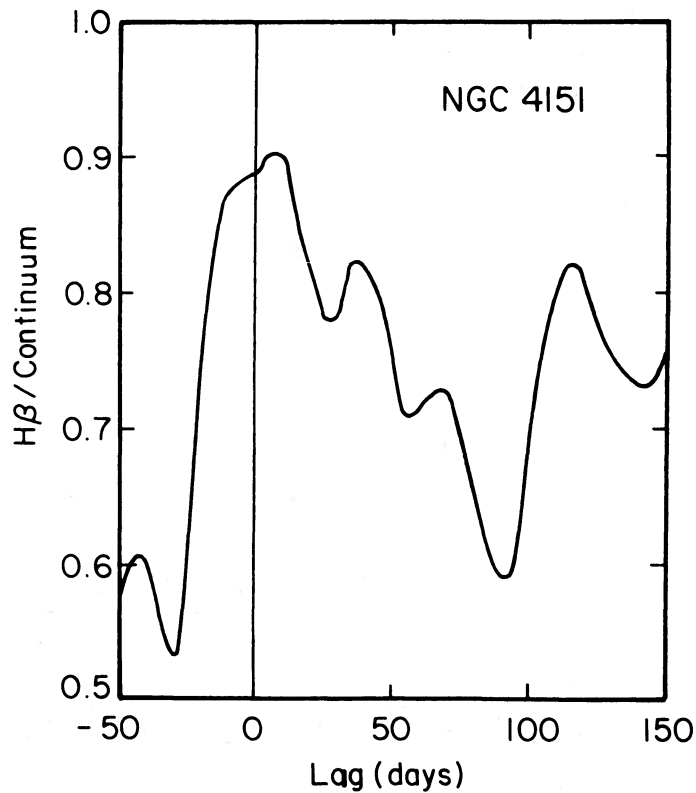


FIG. 4.—Correlation between the Lick Observatory measurements of $H\beta$ $\lambda 4861$ in NGC 4151 and the galaxy-subtracted continuum at 5000 \AA vs. the lag between the line and continuum measurements.

as it would have been interesting to have seen if the emission-line region size has changed over the last decade.

Antonucci and Cohen (1983) were a little more fortunate. The $H\alpha$ variability (rms) in their data was 0.2 mag, but most of this was due to NGC 4151 being in a bright state when they began their monitoring program. The lag is not well determined. In Figure 3 we show the effect of removing the most deviant point (the night on which Antonucci and Cohen estimate the galaxy subtracted continuum to be negative). The lag is somewhere between 5 and 60 days.

ii) *Higher Order Balmer Lines*

Antonucci and Cohen find $H\beta$ and $H\gamma$ to be much more variable than $H\alpha$. In Figures 4 and 5 we show the results of cross-correlating the $H\beta$ and $H\gamma$ fluxes with the continuum. In both cases the secondary peak at ~ 115 days lag is enhanced by the continuum maximum at the start of the observations, and in Figure 5 we show the effect of removing the brightest continuum point. The main peak is insensitive to removing

extreme values; we estimate it to be between 0 and 7 days for $H\beta$ and between 5 and 9 days for $H\gamma$. The higher order Balmer lines are therefore coming mostly from a region ~ 6 lt-day from the variable ionizing source. Note that, as with $H\beta$ in Akn 120 and the UV lines in NGC 4151 (see below), the correlation function has a "tail" to longer lag times (~ 100 days) thus suggesting (as one would expect) that there is significant Balmer line emission from larger radii.

There is a tentative indication that the $H\alpha$ emission is coming from farther out than the higher order Balmer line emission. As well as the larger size suggested by the $H\alpha$ /continuum correlation, the $H\alpha/H\beta$ correlation (not shown) suggests that $H\alpha$ lags $H\beta$ by ~ 13 days.

iii) $He\ II\ \lambda 4686$

We estimate the lag of $He\ II\ \lambda 4686$ to be between -2 days and $+6$ days from the Lick data (see Fig. 6), suggesting that the region producing $He\ II$ is somewhat closer to the photoionizing source than the higher order Balmer lines.

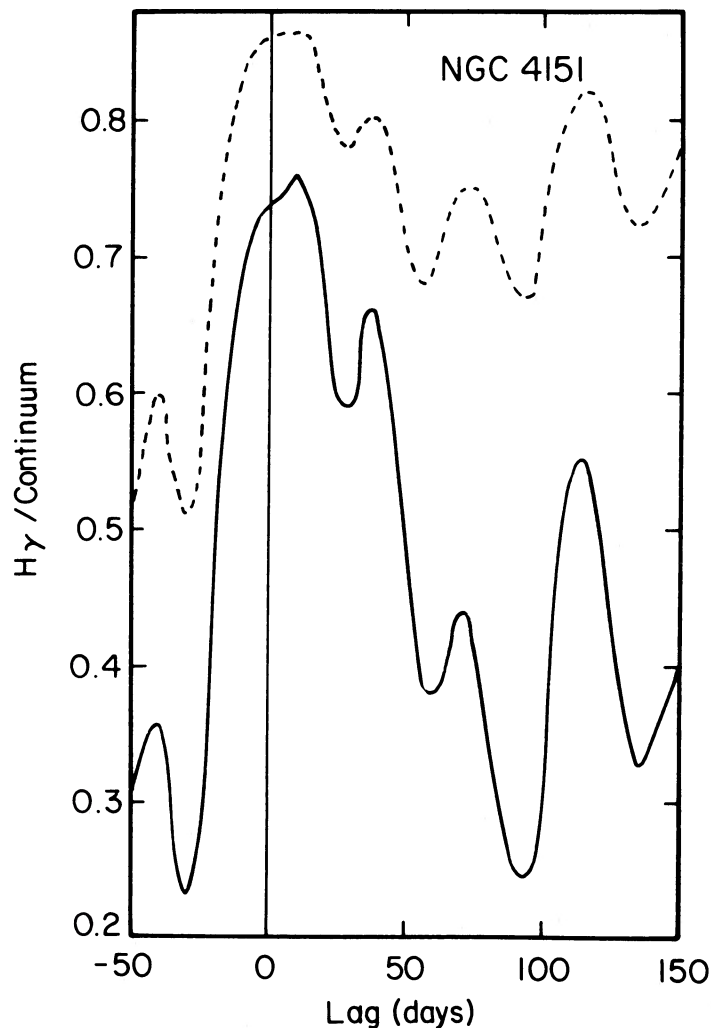


FIG. 5.—Correlation between $H\gamma\ \lambda 4340$ in NGC 4151 and the galaxy-subtracted continuum at $5000\ \text{\AA}$ vs. the lag between the line and continuum measurements (Lick Observatory data). Dashed curve shows the effect of removing the brightest continuum point.

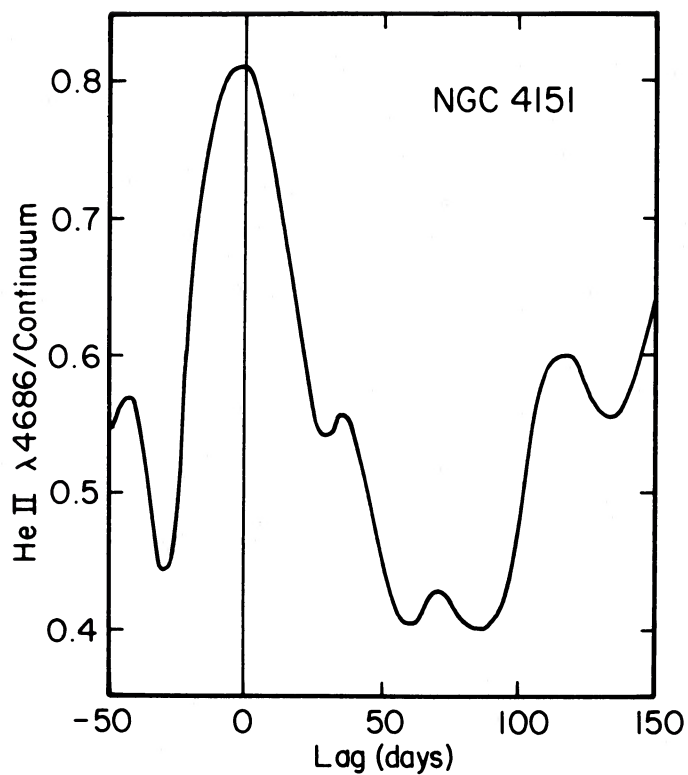


FIG. 6.—Correlation between He II λ 4686 in NGC 4151 and the galaxy-subtracted continuum at 5000 Å vs. the lag between the line and continuum measurements (Lick Observatory data).

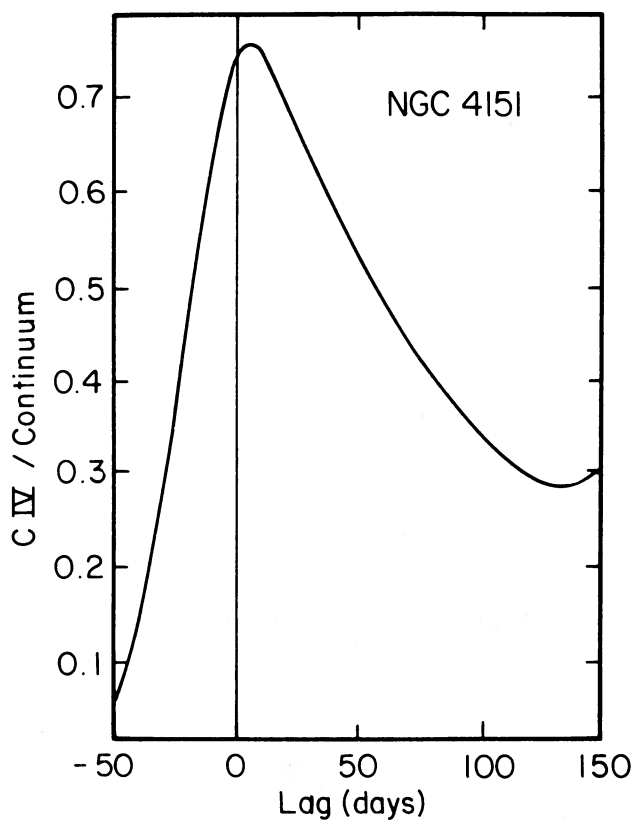


FIG. 7.—Correlation between IUE observations of C IV λ 1549 in NGC 4151 and the continuum at 2500 Å vs. the lag between the line and continuum measurements (IUE data).

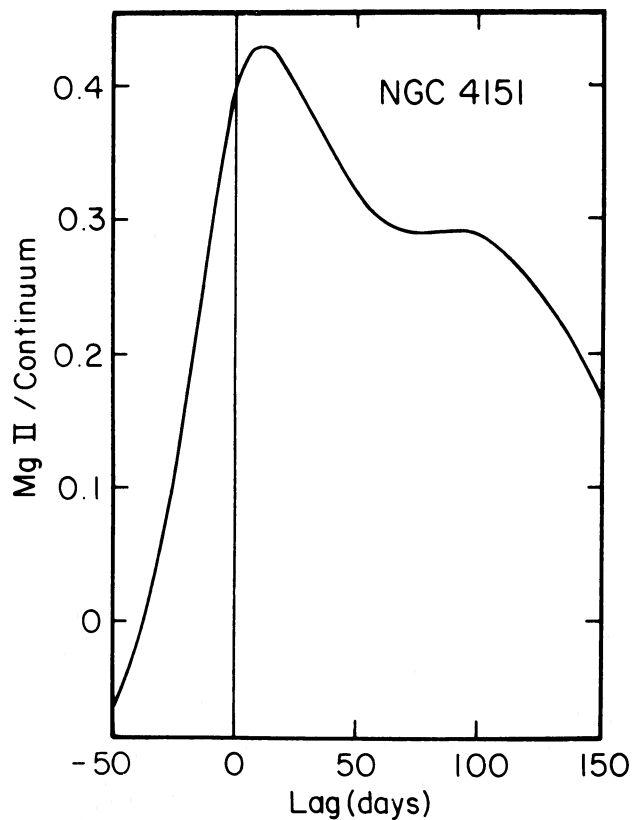


FIG. 8.—Correlation between Mg II λ 2798 in NGC 4151 and the continuum at 2500 Å vs. the lag between the line and continuum measurements (IUE data).

iv) C IV $\lambda 1549$

The *IUE* observations show a strong clear peak in the correlation function at a lag of 5 days (Fig. 7). Removing the most extreme line and continuum points moves the peak to between 6 and 7 days. We are therefore confident that the dominant C IV emission is coming from within 5–7 lt-day of the central ionizing source (i.e., about the same radius as H β and H γ).

v) Mg II $\lambda 2798$

The line/continuum correlation gives a lag of 12 days (Fig. 8). Removing extreme points moves the position of the peak between 8 and 19 days. Mg II is better correlated with C IV than with the continuum (see Fig. 9) and follows C IV by 5 days. We therefore believe that the Mg II emission is mostly coming from 10–12 lt-day from the center and thus twice as far away as the C IV emission. There is a significant “hump” at a lag of ~ 90 –100 days in the Mg II/continuum correlation. This is not caused by any single point in the data and might be real.

vi) $\lambda 1908$ Blend

Although the emission feature near $\lambda 1908$ into quasars has traditionally been regarded as C III] alone, this has been called in question in recent years. Gaskell, Shields, and Wampler (1981) attributed much of the blend to Si III], Al III, and Fe II. Recently Hartig and Baldwin (1985) have proposed that the dominant contributor to the blend is Fe III (see also Wampler 1985). Whatever the ion(s) producing the $\lambda 1908$ blend, the feature appears to lag behind C IV by ~ 8 days (see Fig. 10),

suggesting that it comes from much the same region as the Mg II emission (this is, incidentally, support for the Hartig and Baldwin Fe III interpretation rather than the traditional C III] interpretation). The $\lambda 1908$ /continuum correlation itself (Fig. 11) does not show a very clear peak, and the presence of the peak at ~ 20 days depends largely on a single $\lambda 1908$ observation.

d) Mrk 509

Chapman, Geller, and Huchra (1985) present the results of an *IUE* variability study of a number of other Seyfert galaxies. Only a subset of the observations of one of these galaxies (Mrk 509) is suitable for our analysis. This is a run of *IUE* observations in the fall of 1982 covering a 40 day interval. Ly α and C IV appear lag the continuum by 10–25 days, but this is very uncertain because of the small number of observations.

IV. DISCUSSION

a) Broad-Line Region Densities

Our clearest result is that broad-line regions (BLRs) are considerably smaller than has previously been thought (for example, Cherepashchuk and Lyutyi inferred that the NGC 4151 H α region was ~ 30 lt-day in radius, Ulrich *et al.* suggested it was ~ 1 lt-yr in radius). In the case of Akn 120, Peterson *et al.* (1985) have already emphasized that their estimate of a radius (r_d) of less than 30 lt-day for the H β emitting

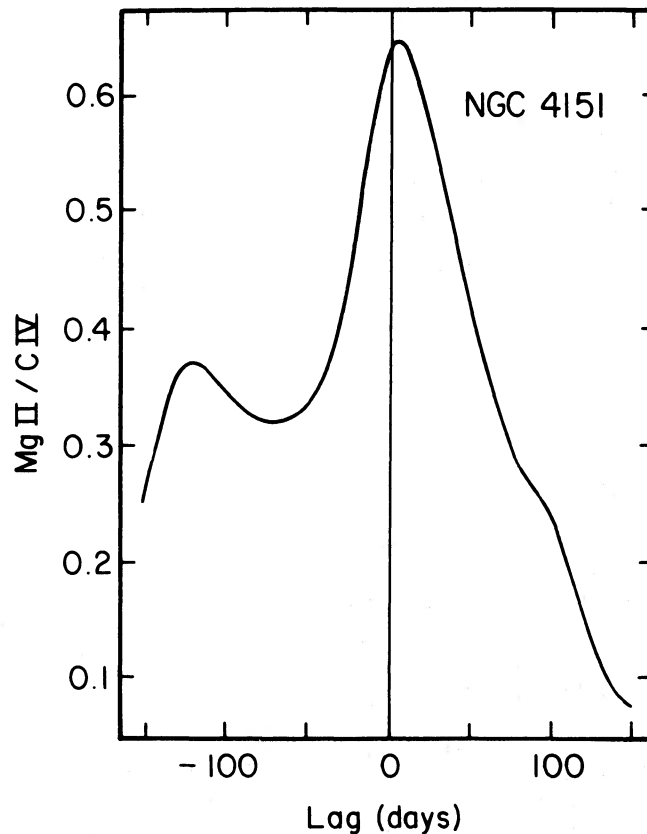


FIG. 9.—Correlation of C IV $\lambda 1549$ with Mg II $\lambda 2798$ vs. lag (in the sense of a positive lag being Mg II correlated with C IV at an earlier time) (*IUE* data)

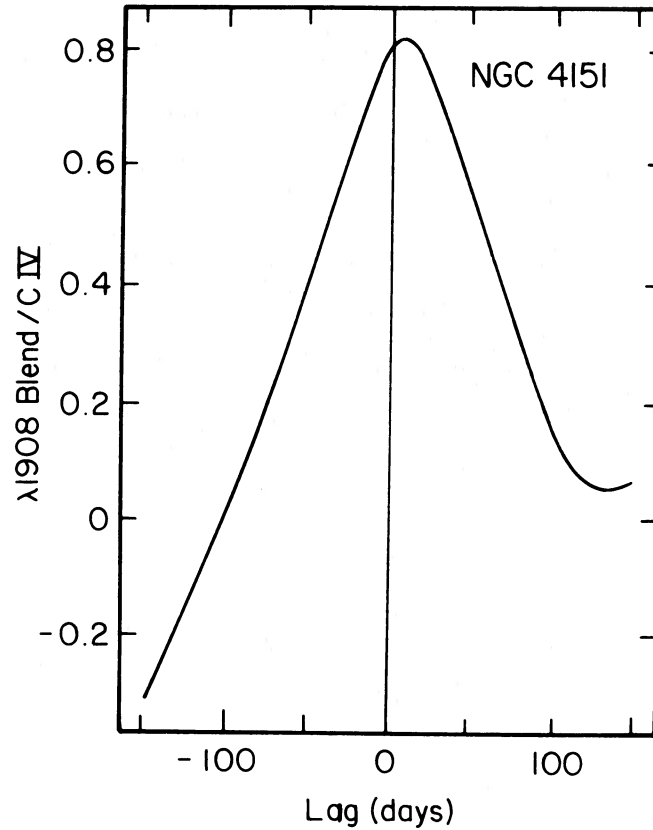


FIG. 10.—Correlation of C IV $\lambda 1549$ with the $\lambda 1908$ blend vs. lag (in the sense of a positive lag being $\lambda 1908$ correlated with C IV at an earlier time) (IUE data)

region forces the density to be considerably higher than in standard photoionization models. Models made over the last decade have favored a “canonical” density of $3 \times 10^9 \text{ cm}^{-3}$. However, substituting our deduced size $r_d \approx 6$ into equation (5) of Peterson *et al.* (1985) gives a density of $\sim 2 \times 10^{12} \text{ cm}^{-3}$ (taking other numbers to be the same as those used by Peterson *et al.*). If our size estimate for Mrk 509 is correct, it too has a BLR density of $\gtrsim 10^{12} \text{ cm}^{-3}$. For NGC 4151 our sizes imply densities of 10^{10} – 10^{11} cm^{-3} (using the results of Ferland and Mushotzky 1982).

b) Stratification of Broad-Line regions

It has long been realized that at least two BLR components are necessary to explain the observed line ratios (Davidson 1977). Gaskell (1982*b*) discovered that the low- and high-ionization lines have different redshifts (and hence profiles). This requires that the cloud motions be radial and that there be some form of obscuration (either internal to the clouds or external). Since the clouds are, most likely, outflowing (see Mathews 1982*b*; Osterbrock and Mathews 1986) this implies that the high- and low-ionization clouds are in separate regions. Shuder (1982) found that He I $\lambda 5876$ was systematically broader than H α and that H β was broader than H α . He argued that this meant that the ionization parameter or density decreased radially outward. Wilkes (1984) found O I $\lambda 1305$ in high redshift quasars to be narrower than the high-ionized UV lines, and Mathews and Wampler (1985) find Mg II $\lambda 2798$ also to be systematically narrower. Ulrich *et al.* (1984) claimed that NGC 4151 had three BLRs: one producing C IV, at a radius of

13 lt-day; one producing Mg II, at a radius of 60 lt-day; and one producing C III], with dimensions exceeding 1 lt-yr. Our results do not support this picture (and it is abandoned in Ulrich *et al.* 1986); Table 1 gives a summary of our best estimates of the radii of *peak* emissivity. The skewness of almost all the line/continuum correlations suggests (as one would expect) that there is significant emission from larger radii (out to at least 100 lt-day).

Our peak emissivity radii divide roughly into two groups. The small radii of H β /H γ emission is perhaps a little surprising. We must caution that Balmer sizes were deduced from data taken the *year after* the IUE observations. At the time of the Lick observations NGC 4151 was less active than at the time of

TABLE 1
SUMMARY OF MOST LIKELY RADII OF PEAK
EMISSIVITY IN NGC 4151

Ion	Radius (lt-day)
High-ionization filaments:	
He II	2
C IV	5
H β , H γ	6
Low-ionization filaments:	
Mg II	12
$\lambda 1908$ blend	16
H α	20?

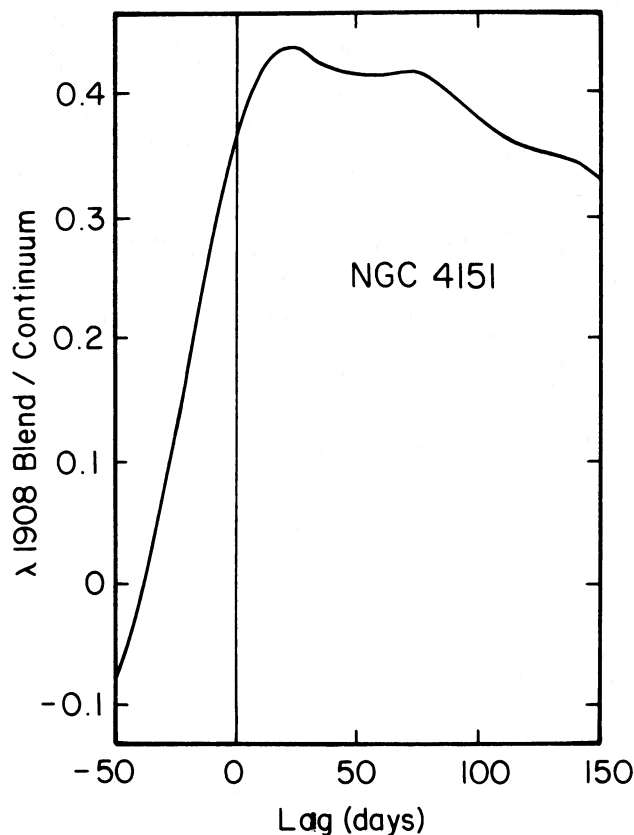


FIG. 11.—Correlation between the $\lambda 1908$ blend in NGC 4151 and the galaxy-subtracted continuum at 2500 \AA vs. the lag between the line and continuum measurements (*IUE* data).

the *IUE* observations. The BLR might have been smaller when NGC 4151 was less active. Mathews and Capriotti (1985) point out that the NGC 4151 BLR might never achieve the steady state seen in more luminous quasars, but since the crossing times of the BLR at typical velocities of $\sim 10,000 \text{ km s}^{-1}$ are of the order of 1 yr or so, the gas distribution cannot change drastically. The $H\beta$ size we found for the slightly intrinsically brighter Seyfert Akn 120 was also ~ 6 days. If we believe Table 1, it suggests that BLR material resembles more the swarm of arbitrarily small filaments considered by MacAlpine (1972) rather than the large “typical” clouds in fashion more recently. Appropriate scaling of MacAlpine’s 1972 results to higher densities indeed gives good agreement between the predicted radii of peak emissivity and the values in Table 1. The parabolic orbit model of Carroll (1985) gives similar agreement.

c) Kinematic Mapping

Although the weight of the evidence points to outward radial motion of BLR filaments, the objection has been raised (e.g., by Ulrich *et al.* 1984) that although profiles do change, the blue side of emission lines does not always brighten first when the continuum brightens. This has often been taken as evidence

for chaotic motions of the clouds. However, if the BLR is as small, as we find it to be, then the rise times of “flares” in Seyfert galaxies (Lyutyi 1977) are *longer* than the BLR light crossing times; we do not then expect to see large systematic effects in the line profiles.

Akn 120 is an example of a Seyfert with a double-peak Balmer-line profile. Capriotti, Foltz, and Peterson (1982) proposed that the line profile structure could be explained by continuum variability if the light crossing time was ~ 2.7 yr. Gaskell (1983) argued that the constancy of the wavelengths of the displaced broad line peaks over long periods of time (> 15 yr in one case) rules out such an explanation, and proposed instead that objects such as Akn 120 had binary BLRs, each one with an associated black hole. The small BLR sizes implied by the more recent Ohio State data rule out the Capriotti *et al.* (1982) explanation. It would be very interesting to see if one of the two peaks in the Akn 120 $H\beta$ profile lagged the continuum variability by significantly more than the main BLR size (e.g., 100 days or more). The second peak in Figure 2 is the sort of feature in the correlation function one would expect from the binary model, but its reality needs to be confirmed.

d) Future Observations

The small sizes we find for Seyfert BLRs suggest that monitoring needs to be more frequent than it has been in the past.¹ Seyfert galaxies need to be monitored every few days to get higher precision in measuring sizes. This slightly closer spacing coupled with longer sequences of observations (say 50 or 60) will also permit one to start to recover the radial distribution for a single ion. The good news for observers (particularly writers of NSF grants and Ph.D theses, etc.) is that significant results can be obtained in less than one observing season!

V. CONCLUSIONS

1. For a spherical distribution of filaments the maximum response to an instantaneous flare in the continuum (a spike in the light curve) occurs *immediately*.
2. The rise times of broad emission lines cannot be used to deduce the sizes of the emitting regions since different lines respond differently to changes in photoionizing continuum flux. Cross-correlation methods should be used instead.
3. We find BLR sizes as small as a few light days in NGC 4151 and Akn 120. These small sizes imply densities an order of magnitude or two higher than in current “standard” models.
4. The emission lines coming from regions of lower ionization have their peak emissivities coming from several times further out than the high-ionization lines.

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¹ It might surprise some readers that we can measure lags to accuracies of a few days with a typical sampling intervals of 20–30 days, but this is really little different from measuring a radial velocity to an accuracy of, say, $\pm 20 \text{ km s}^{-1}$ from a spectrogram with a resolution of 500 km s^{-1} .

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