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**The nature of emission-line profile variability and the structure
of the line-emitting regions in active galactic nuclei**

Korista, Kirk Thomas, Ph.D.

The Ohio State University, 1990

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Ann Arbor, MI 48106

THE NATURE OF EMISSION-LINE PROFILE VARIABILITY AND THE STRUCTURE
OF THE LINE-EMITTING REGIONS IN ACTIVE GALACTIC NUCLEI

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of the Ohio State University

By

Kirk Thomas Korista, B.S.

* * * * *

The Ohio State University

1990

Dissertation Committee:

Bradley M. Peterson

Gary J. Ferland

Eugene R. Capriotti

Approved by

Advisor
Department of Astronomy

To Angela, David, and Phillip

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VITA

February 13, 1963	Born -- Urbana, Illinois
1984-85	Teaching associate, The University of Illinois at Urbana- Champaign, Illinois
1985	B.S., The University of Illinois at Urbana-Champaign, Illinois
1985-Present	Teaching Associate, Research Associate, Perkins Observatory Fellow, Presidential Fellow at the Ohio State University, Columbus, Ohio

PUBLICATIONS

"The Double Broad-Line Emitting Regions in NGC 5548 as Possible Evidence for a Supermassive Binary", B.M. Peterson, K.T. Korista, and S.A. Cota 1987, *Ap.J. (Letters)*, 312, L1.

"The Evolution of the Radio Emission from Kepler's Supernova Remnant", J.R. Dickel, R. Sault, R.G. Arendt, Y. Matsui, and K.T. Korista 1988, *Ap.J.*, 330, 254.

"The Origin of Coronal Lines in Seyfert Galaxies", K.T. Korista and G.J. Ferland 1989, *Ap.J.*, 343, 678.

"Continuum and Emission Line Variability of the Seyfert Galaxy Arakelian 120: Analysis of a Large Data Base", B.M. Peterson, K.T. Korista, and R.M. Wagner 1989, *A.J.*, 98, 500.

"Ultraviolet and Optical Spectroscopy of NGC 5548 and the Nature of the Broad-Line Region", B.M. Peterson, G.A. Reichert, K.T. Korista, and R.M. Wagner 1990, *Ap.J.*, 352, 68.

FIELDS OF STUDY

Major Field: Astronomy

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the nature of the very broad line emitting region in active galactic nuclei (G.J. Ferland, B.M. Peterson)

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CHAPTER I

INTRODUCTION

I. Active Galactic Nuclei

The most energetic objects in the universe, active galactic nuclei (AGN) emit their energy within an incredibly small volume of about one cubic parsec ($1 \text{ parsec} \approx 3.086 \times 10^{18} \text{ cm}$) or less. In addition the energy emitted is non-stellar in origin. All studies of AGN are ultimately trying to answer the same question: *"What is the energy source?"* Because they are very distant, AGN also give us a view of the universe in the distant past, to within one billion years after the formation of the universe. Thus AGN provide a probe of the evolution of the universe.

Only a small fraction (a few percent) of all known galaxies have AGN, which exhibit a wide variety of characteristics. However, most AGN have at least two features in common. The first is non-stellar continuum emission, which is observed from radio to X-ray and sometimes gamma ray frequencies, and may be comparable in luminosity (10^{41} - $10^{45} \text{ ergs s}^{-1}$) to the galaxy within which it resides (low luminosity AGN or LLAGN), or which may completely overwhelm the light from the rest of the galaxy (10^{46} - $10^{48} \text{ ergs s}^{-1}$; high luminosity AGN or HLAGN). The second common feature of almost all AGN is the presence of bright emission

lines with a wide range of ionization in their spectra in addition to, in the LLAGN, stellar and interstellar absorption lines which characterize the spectra of normal galaxies. These emission lines have widths (10^2 - 10^4 km s⁻¹ full-width at half maximum or FWHM) much larger than that which can be accounted for by thermal motions, and are probably Doppler-broadened through bulk motions.

AGN have been placed into categories of observed common characteristics, generally related to their continua and/or their emission lines. Starting at the extreme low luminosity end of the AGN are the LINERs (Low Ionization Nuclear Emission Regions), which may be the low luminosity end of the class of AGN known as the Seyfert type 2 galaxies. These AGN display "narrow" permitted and forbidden emission lines (10^2 - 10^3 km s⁻¹ FWHM), which are actually as broad or broader than widths due to normal galactic motions (100-200 km s⁻¹ FWHM). The generally more luminous Seyfert type 1 galaxies have similar narrow forbidden lines, but their permitted lines are much broader (10^3 - 10^4 km s⁻¹ FWHM). In addition they display a strong "blue" continuum (observable in Seyfert 2s, though weaker). The optical light in the central regions of most normal galaxies is dominated by late-type giant stars which have continua rising toward the red, instead of the blue, as observed in active galactic nuclei. However, note that most "blue" galactic nuclei discovered are the so-called "starburst galaxies" which have large population of early-type stars in their nuclei, as opposed to Seyfert galaxies whose blue light is mainly non-stellar in origin. The narrow and broad line radio galaxies (NLRGs and BLRGs) are the radio "bright" (i.e., rather luminous at radio frequencies) counterparts to

the Seyfert 2 and Seyfert 1 galaxies. At high luminosities are the quasi-stellar objects (QSOs). Here the surrounding galaxy is rarely observed against the extremely bright active nucleus. The radio "quiet" QSOs and the radio "loud" QSOs are apparently the more distant and luminous cousins to the Seyfert 1s and BLRGs, respectively. In addition there is a class of radio quiet QSO which displays broad, blueshifted, absorption lines in addition to the broad emission lines. These are known as the broad absorption line QSOs (or BALQSOs). Finally, the "blazars" are a class of generally radio loud QSOs which display violent activity in their continua and sometimes emission lines. This class includes the BL-Lac objects in which the emission lines are extremely weak or absent, the high polarization QSOs (HPQs), and the optically violently variable QSOs (OVVQs).

II. The Emission Lines as Probes of AGN

Much of what we know about AGN is from the analysis of the emission lines: emission line strengths, ratios, profiles, and variability among all three. The following are examples of what has been discovered about AGN through the study of their emission lines.

As implied by the two types of emission lines (narrow and broad), there are two separate emission line regions. The larger one is the narrow line region (NLR) which lies $\sim 10\text{-}10^3$ parsecs (pc) from the central continuum source (also known as the central "engine"). Because of the presence of strong narrow forbidden lines the electron densities must be less than $\sim 10^6\text{ cm}^{-3}$ in the NLR. On the other hand the broad line region (BLR) is known to be much denser ($> 10^8\text{ cm}^{-3}$) because of the

absence of strong broad forbidden lines. The presence of strong broad semi-forbidden lines such as C III] λ 1909 is indicative that in the regions within the BLR where these lines are formed the densities are not much higher than 10^{10} cm^{-3} . At densities much larger than this the broad semi-forbidden lines become collisionally suppressed. The BLR also lies much nearer to the central continuum source, from much less than 1 pc to perhaps ~ 1 -10 pc. Although the broad lines are not observed in total integrated light in Seyfert 2 galaxies, it has been shown (Antonucci and Miller 1985; Miller and Goodrich 1990) that broad line emission may be observed in polarized light in some of these objects, implying the presence of some source of obscuration and a scattering medium. Thus the distinction between the two types of Seyfert galaxies is not quite so clear. We note here that there are no known "QSO type 2s". The emission line gas in the broad and narrow line regions is almost certainly photoionized to a temperature of $\sim 10^4$ K by the central continuum source or sources whose origin is uncertain; although it is thought to be powered by accretion of matter onto and the rotation of a 10^6 - 10^9 solar mass black hole. The origin of the emission-line gas (gas clouds, bloated stars, or something else) is unknown.

In addition to being predictors of the physical conditions of the emitting gas, emission line strengths and ratios may also indicate the strength and shape of the mainly unobservable ionizing continuum. For example, Binette *et al.* (1989) and Clavel and Santos-Lleo (1990) were able to predict, through the behavior of the flux ratio $L\alpha/\text{C IV } \lambda 1549$ with the ultraviolet continuum, that the ionizing continuum must

substantially weaken beyond ~ 1 Rydberg in Seyfert 1 galaxies.

Below we describe the studies undertaken in this Dissertation of two emission line regions within active galaxies, using the emission lines as probes of the structure of the emitting gas.

A. The Broad Line Region

Much of this Dissertation is devoted to an analysis of the broad emission lines. By studying the broad emission lines we hope to determine constraints on the important physical processes occurring within a region very near to the central engine. For example, the knowledge of the structure and dynamics of BLR and the radiation field within the BLR can provide important clues as to the nature of the central engine itself. Because of its proximity, the structure and dynamics of the broad line gas may be indicative of the geometry, dynamics, and mass of the central engine, while the radiation field within the BLR may tell us how the central engine is radiating. In this Dissertation I investigate the structure of the broad line emitting gas in both low and high luminosity AGN, specifically in Seyfert 1 galaxies and radio quiet QSOs. The large distances to AGN and the small physical size of the BLR mean that BLR cannot be spatially resolved in any AGN and thus we cannot study it directly. Two indirect methods of investigating the structure of the BLR are utilized.

1. Broad Emission Line Flux Variability

The continuum has been known to be variable in all luminosity classes of AGN for over 25 years. If the broad emission lines are indeed driven through photoionization via the central continuum source,

then some variation in the strengths of the broad emission lines should be observed as long as the gas is radiation bounded and the timescale for continuum variability is long compared to the recombination timescale

$$\tau_{\text{rec}} \sim (\alpha_{\text{rec}} N_e)^{-1} \approx 4 \times 10^{12} N_e^{-1} \text{ seconds} \quad (1),$$

where α_{rec} is the recombination coefficient and N_e is the electron density. For BLR densities this corresponds to a recombination timescale of minutes to hours. A large BLR also cannot react coherently to a "flickering" continuum source; i.e., no changes in the broad line flux can be observed if the timescale for continuum variability is very short relative to the light travel time across the BLR. Because of the finiteness of the speed of light, an external observer does not observe the entire BLR to respond immediately to a change in the ionizing continuum. Nor would he or she observe isotropically emitted continuum pulses as spherical shells propagating through the BLR. The distant observer would see these pulses as paraboloidal shells, whose surfaces are those of constant time delay. In addition the observed response of the emission lines to a change in the continuum is a function of the distribution of the broad line gas about the central continuum source. Specifically, the emission line response is the convolution of the continuum intensity as a function of time with the transfer function, which contains the information of broad line gas distribution. Thus, given enough information about the continuum and emission line intensities as a function of time (assuming the broad line fluxes change), the distribution of the broad line region gas may be determined

through inversion of the aforementioned convolution equation (Blandford and McKee 1982).

a. The Low Luminosity AGN

Since the confirmation of broad emission line variability in LLAGN (Penston *et al.* 1981; Peterson *et al.* 1982), many spectrophotometric variability studies have been done in an attempt to determine the size and geometry of the broad line regions in these objects. Some examples of these studies are: Fairall 9 (Clavel, Wamsteker, and Glass 1989; Koratkar and Gaskell 1989), Arakelian 120 (Peterson *et al.* 1985; Peterson, Korista, and Wagner 1989; Peterson and Gaskell 1990), NGC 4151 (Clavel *et al.* 1987, 1990a; Maoz *et al.* 1990a), Markarian 279 (Maoz *et al.* 1990b), and NGC 5548 (Peterson 1987; Peterson, Korista, and Cota 1987; Stirpe, de Bruyn, and van Groningen 1988; Peterson *et al.* 1990a; Netzer *et al.* 1990; Wamsteker *et al.* 1990; Clavel *et al.* 1990b; Peterson *et al.* 1990b). A recent international collaboration to monitor NGC 5548 at ultraviolet and optical wavelengths (Clavel *et al.* 1990b; Peterson *et al.* 1990b) has resulted in the extraction of the transfer function for a number of broad emission lines (Horne, Welsh, and Peterson 1990; Krolik *et al.* 1990).

In photoionization models the size of the BLR is defined through the ionization parameter

$$U = \frac{Q}{4\pi R^2 N_H c} \quad (2),$$

where Q is the number of ionizing photons emitted per second by the central continuum source, R is the distance to the inner edge of the BLR

gas "cloud" from the source of ionizing photons, N_H is the particle density in the broad line clouds, and c is the speed of light. About ten years ago a "standard" photoionization model for the BLR was developed which matched many of the observed spectral characteristics (Davidson and Netzer 1979; Kwan and Krolik 1981). The standard model predicts an ionization parameter of ~ 0.01 . However, with the exception of Fairall 9, most of the above broad emission line variability studies have strongly indicated that the broad line regions of Seyfert 1 galaxies are smaller than those predicted by the standard model by factors of $\sim 5-10$ (see review by Peterson 1988). The smaller BLRs in LLAGN imply larger ionizing photon fluxes incident upon the BLR gas and thus larger ionization parameters than predicted by the standard model, unless the densities are significantly larger. This in turn means that we may have to reconsider many of our ideas about emission line formation in the broad line region. More recent models have investigated larger densities (Rees, Netzer, and Ferland 1989), larger ionization parameters (Netzer 1987; Ferland and Persson 1989), and multiple emitting components (Netzer 1987; Collin-Souffrin *et al.* 1988), although many problems still remain (see review by Netzer 1989).

b. The High Luminosity AGN

One of the more remarkable observed characteristics of broad emission line AGN is the similarity of their broad line equivalent widths, although their luminosities may differ by factors exceeding 10^2 . According to the standard model this indicates a common ionization parameter, which implies that the BLRs of the HLAGN ought to be more

than 10 times larger in these objects than in LLAGN (i.e., ~ 10 light years). Little, if any, variability in the broad emission line fluxes in the HLAGN was expected, and in any case only on very long timescales. However, recently such variability on timescales of less than one year have been recently reported (see, for example, Gondhalekar 1990). This needs to be confirmed before more intensive variability studies, such as those for the LLAGN, can be carried out. As described in Chapter II of this Dissertation I have undertaken a study to see if the previous, and in some cases controversial, reports of short timescale broad line flux variability in HLAGN could be confirmed.

2. Broad Emission Line Profile Variability

The broad emission lines of several Seyfert 1 galaxies are known to be variable in time. The construction of broad emission line difference spectra (e.g., subtracting one H β profile from another) and comparisons of profiles of different species have suggested that the BLRs in at least some AGN may have multiple line emitting components (Ulrich and Boisson 1983; Peterson et al. 1990a; Wamsteker et al. 1990). The individual broad line components may represent completely separate BLRs, as suggested by Peterson (1987) and Peterson, Korista, and Cota (1987), or they may represent emitting regions that are spatially and kinematically separate but are part of the same BLR (e.g., accretion disk and wind), or perhaps they are just emissivity inhomogeneities within the same dynamical structure. Furthermore, excitation inhomogeneities propagating across the BLR due to a continuum pulse can produce a similar pulse through the broad line profile, as long as the

velocity field is not position independent (Capriotti, Foltz, and Peterson 1982). If such a pulse is temporally resolved with high quality data, the dominant motion of broad line gas flow (e.g., inflow, outflow, rotation) may be determined. Thus the analysis of the variability of the broad emission line profiles may be a useful probe of the structure of the BLR. Important questions that need to be answered are: (1) Can the components be isolated (positions, widths)? (2) Is their behavior correlated with the behavior of continuum or with each other, and if so how? (3) What are the timescales for profile variations? (4) Do flux ratios between different emission lines, which indicate the physical conditions of the emitting gas, differ among the components? (5) Can particular kinematical models (jets, wind, accretion disk, inflow, outflow, rotation, etc.) be identified or excluded? In Chapters III and IV of this Dissertation, the broad emission line profiles and their variability are analyzed to set constraints on the structure of the broad line regions in two Seyfert 1 galaxies, Arakelian 120 and Markarian 590. In the case of Markarian 590 a photoionization code was utilized to further investigate the properties of one of the components that, through an *extreme* variation in the overall broad line profile, was well isolated.

B. The Coronal Line Region

There is another class of forbidden lines observed in AGN spectra known as the coronal lines, named after similar emission lines seen in our Sun's corona. Very little is known about the origin of these high excitation, weak forbidden lines of iron (Fe VII, Fe X, Fe XI, Fe XIV)

and other atoms. The location and extent of the coronal line emitting gas, its density, temperature, and ionization mechanism(s) are all unknowns. What is known is that the widths of these emission lines and the densities at which collisional deexcitation becomes dominant are intermediate between those of the lower excitation narrow lines and the broad permitted lines. Few observations of these lines have been made and few if any self-consistent theoretical models of the coronal line region (CLR) exist. In Chapter V of this Dissertation, utilizing a photoionization code, I investigate the possibility that the coronal line region in AGN may be the result of the "warm phase" ($N_e \sim 1 \text{ cm}^{-3}$) of a galactic interstellar medium exposed to, and subsequently photoionized by, a "bare" AGN central continuum source. The predicted coronal line strengths and ratios are compared to those observed in the Seyfert 1 galaxy NGC 4151. If the coronal lines are in fact due to photoionization by the central continuum source, they may serve as a probe of the unobservable ionizing continuum between ~ 3 and ~ 30 Rydbergs. Little is known of how the active nucleus interacts with the surrounding galaxy. The results of this model shed some light on this.

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CHAPTER II

SHORT TIMESCALE BROAD EMISSION LINE FLUX VARIABILITY
IN HIGH LUMINOSITY ACTIVE GALACTIC NUCLEI

I. Introduction

Because the broad emission line regions in high luminosity active galactic nuclei (HLAGN), or quasi-stellar objects (QSOs), were thought to be very large, little or no variability in the broad emission lines was expected. However, reports of significant broad emission line variability in HLAGN on timescales of less than ~ 1 year started to appear in the literature in 1986 (Gondhalekar, O'Brien, and Wilson 1986; Zheng and Burbidge 1986). Since then further reports have been made (Zheng *et al.* 1987; Gondhalekar 1987; O'Brien, Zheng, and Wilson 1989; Perez, Penston, and Moles 1989; Gondhalekar 1990), and the strong possibility of such variability in HLAGN can no longer be ignored. Here we describe a study undertaken to see if broad emission line flux variations in HLAGN on these short timescales could be confirmed. In Section II we describe the observations. We present the results in Section III and a discussion and summary follows in Section IV.

II. The Observational Program

A. The Program Goals

A relatively large sample of QSOs were to be systematically observed spectrophotometrically at predetermined intervals on timescales of 1 year and less. QSOs have been observed in this way for broad emission line variability only once before (Perez, Penston, and Moles 1989) for a sample of 6 *radio-loud* QSOs. Here 12 *radio quiet* QSOs were chosen to be observed on 2 separate timescales: 2-3 months and 9-12 months. It was not our intention to determine the size of the BLRs of QSOs, rather this was to be a preliminary investigation into determining whether the broad emission lines of high luminosity AGN (HLAGN) do indeed vary on timescales of ~ 1 year or less as had been recently reported (however, note that continuum variations in QSOs have been known for ~ 25 years). With a relatively large number in the sample (12) we also wanted to establish just how prevalent the short timescale broad emission line variability in HLAGN is.

We wanted to acquire higher quality data than that upon which most other reports of HLAGN broad emission line variability were based, with convincing results at some reasonably low level of variability ($\sim 15\%$). This kind of data is attainable with the Ohio State University CCD spectrograph on the 1.8m Perkins telescope of the Ohio State University and Ohio Wesleyan University at the Lowell Observatory, and using a nearby constant narrow line for internal flux calibration. This program has the advantage over earlier studies in one or more of the following ways: (1) the data are of higher signal to noise; (2) we do not need to rely on absolute spectrophotometry; we require only relative

fluxes calibrated internally with a nearby constant narrow line; (3) the QSOs are systematically sampled on predetermined timescales.

However, a few setbacks occurred in the implementation of the then newly built CCD spectrograph, and the program had to be scaled back due to time constraints. Fewer objects (8) were observed less frequently. Only 5 objects were observed on timescales of 2-3 months and 5 objects on the timescale of 9-12 months, including an Image Dissector Scanner (IDS) observation made in the Autumn of 1987. Note that not all of the 8 objects were observed on each timescale. However, any discovery of broad emission line variations would be significant, and the project went forth as described below.

We chose to observe the broad Balmer emission line $H\beta$ $\lambda 4861$ for the following reasons. In order to put all of the data from each object on the same flux scale (in general they will not be on the same scale due to the grey extinction of clouds), we scale the data to the flux of the nearby forbidden $[O\ III]\lambda 5007$ line, which is not expected to vary on the timescales of interest. Without this scaling capability made available by the nearby constant $[O\ III]$ line, we would have to rely on acquiring absolute instead of relative spectrophotometry. This is the most important reason for our choice of broad emission line. The last two reasons are more incidental: $H\beta$ is a relatively strong broad emission line, and with the available instrumentation we could in principle observe it in QSOs of redshifts just under 1.0, giving us a large number of QSOs from which to choose.

B. QSO Selection Criteria

High luminosity AGN have a wide range in observed characteristics. Those of common traits are often put into their own category, such as: radio quiet QSOs, radio loud (steep and flat spectrum) QSOs, blazars (BL-Lac objects, optically violently variable QSOs [OVVQs], and high polarization QSOs [HPQs]), and broad absorption line QSOs (BALQSOs). In addition they also come with a variety of brightnesses, apparent and intrinsic. To optimize the quality of the data and to constrain as much as possible the range in interpretations of the results, the sample of QSOs in this study was carefully chosen from Hewitt and Burbidge (1987) according to the selection criteria described below:

Luminosity.---All AGN in this study are brighter than $M_B = -22.1$ (for $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$), which defines the distinction (real or not) between Seyfert 1 galaxies and QSOs (see, for example, Osterbrock 1988).

Apparent Magnitude.---The QSOs in the sample were required to have apparent magnitudes brighter than 17 mag in order to acquire a desirable signal to noise in a reasonable integration time (≤ 2 hours).

QSO Redshift.---As stated above we may observe $H\beta$, $[O \text{ III}]\lambda 5007$ and some surrounding continuum in those QSOs with $z < 1.0$. However, in order to avoid the telluric absorption bands, we restricted the redshifts to $z \leq 0.34$.

[O III] and Fe II Emission.---In order to put the spectra on the same flux scale, we must measure the $[O \text{ III}]\lambda 5007$ flux with reasonable accuracy. Thus we avoided those QSOs with weak $[O \text{ III}]\lambda 5007$. In addition we wanted to avoid those QSOs with strong broad permitted Fe II

emission, which in the form of ($m42$) $\lambda\lambda 4924, 5018$ (and other multiplets as well) often muddles the spectrum near the red wing of $H\beta$, significantly contaminating the [O III] lines, while the Fe II $\lambda 4570$ and $\lambda 5250$ blends can confuse the placement of the continuum near $H\beta$. Both criteria were checked through a literature search for previously published spectra.

Radio Properties.---We required the QSOs in our sample to be radio quiet, in contrast to the monitoring program of Perez, Penston, and Moles (1989) in which all the objects were radio loud. This means we excluded radio selected objects (3C, 4C, and PKS objects), and additionally BL-Lac objects, HPQs, and OVVQs. All of these type of QSOs are thought to have at least some fraction of their observable continua beamed (in many cases along or near our line of sight), while there is no evidence for continuum beaming in radio quiet QSOs. If a significant fraction of the exciting continuum is beamed, then the light curves of the variable continuum and the variable broad emission lines tell us nothing about the size and little about the structure of the BLR in HLAGN, which are ultimately the questions we want to answer. All but four in our (original) sample of 12 are ultraviolet (UV) excess objects (PG and US surveys), three are X-ray selected objects, the last an NAB object (a QSO found lying in the direction of an Abell cluster). All are radio quiet.

C. Observations and Data Reduction

Most of the observations presented here were obtained with the Ohio State University CCD spectrograph on the 1.8m Perkins telescope of the

Ohio State University and Ohio Wesleyan University at the Lowell Observatory. The CCD is a *Texas Instruments 4849* 400x580 chip, and it is mounted on a Boller and Chivens spectrograph. The 350 lines per millimeter grating used (at first order) has 1100Å coverage, and when coupled with a 5 arcsecond slit width, results in a spectral resolution of 9Å. The slit was oriented east-west (PA 90°) for all observations. The wide slit was employed to ensure that most or all of the light fell into the slit, even on nights of fair or poor seeing. Typical seeing was 2-3 arcseconds, although one night (JD 2447848) the seeing varied between 3 and 5 arcseconds. Because of the large distances of these objects, it was not expected that aperture effects, due to the interplay of guiding/seeing effects and extended [O III] often observed in Seyfert galaxies, would be a problem in this study. However, to be absolutely certain the large 5" slit was used. Sky conditions were generally clear with thin cirrus; only one night (JD 2447573) was deemed to be photometric. Individual exposure integration times were 1800 seconds, and usually 3-4 exposures were taken per object. This resulted in signal to noise ratios of typically 40-65, although a couple observations were in the 20-30 range (e.g. 1E0357+107). An order separating filter was used when necessary to block out second order blue light. A log of the observations is given in Table 1. The object name, redshift, the Julian Date of observation, the total integration time, and the instrument used are listed in columns 1-5, respectively.

Table 1
Log of the Observations

QSO	z	Julian Date (2440000+)	Integration Time (s)	Instrument
(1)	(2)	(3)	(4)	(5)
PG0026+129	0.145	4553	1600	IDS
		7413	3600	IDS
		7778	5400	CCDsp
		7848	5400	CCDsp
PG0052+251	0.155	7778	5400	CCDsp
		7847	5400	CCDsp
PG0157+001	0.163	7788	5400	CCDsp
		7848	7200	CCDsp
NAB0205+024	0.155	4553	1600	IDS
		7783	5400	CCDsp
		7847	5400	CCDsp
1E0357+107	0.182	7572	5400	CCDsp
		7848	7200	CCDsp
1E0514-001	0.292	7560	5400	CCDsp
		7573	7200	CCDsp
		7849	7200	CCDsp
0833+446	0.255	7534	3600	CCDsp
		7560	7200	CCDsp
		7572	5400	CCDsp
		7849	7200	CCDsp
PG0906+484	0.118	7571	5400	CCDsp
		7572	5400	CCDsp
		7573	7200	CCDsp
		7848	7200	CCDsp
		7915	7200	CCDsp

The CCD data were reduced in the usual way with IRAF. Every CCD frame contained a 20 millisecond preflash which, along with the the bias level, was subtracted from the data. Several quartz lamp exposures were taken for every grating setting to remove the CCD pixel to pixel variations. One to two iron-neon lamp and standard star exposures were taken per object per night to wavelength and flux calibrate the extracted spectra. All program objects, including standard stars, were observed along the same column on the CCD chip. This column ($\pm$ few pixels) corresponds to the center of the chip where the slit illumination profile is relatively constant for ~ 100 pixels on either side. Thus no sky flats were necessary to determine the slit illumination profile. The background was carefully fitted along either side of the object and subtracted off during the extraction of the data to one dimension.

A few of the observations were obtained with the Ohio State University Image-Dissector Scanner (IDS) (Byard *et al.* 1981) on the same telescope with 7 arcsecond circular entrance apertures and reduced as described by Peterson (1987). These data are from the OSU IDS data archive, and were not part of the observing program outlined above. However, these data could be used to investigate variability on longer timescales, and 1 of the 3 IDS observations was taken (PG0026+129: by the author) only 1 year prior to the first CCD observation of PG0026+129. These data are also listed in Table 1.

III. The Results

A. Measurements

As discussed above all data for each QSO were scaled to the same flux in $[O\ III]\lambda 5007$. In addition difference spectra were formed for each QSO data set, and the residual was checked for any evidence of the $[O\ III]$ lines. In all cases $[O\ III]\lambda 5007$ is contaminated with Fe II ($m42$) $\lambda 5018$; however, the contamination is weak as these objects were selected against strong optical Fe II emission. In all cases the chosen flux scales resulted in minimum $[O\ III]$ residual, demonstrating that weak Fe II did not confuse the flux measurement of the $[O\ III]\lambda 5007$ line (to the level of accuracy that we are looking for, namely, better than $\sim 10\%$). One must keep in mind that we do not require the absolute flux of $[O\ III]$, and in general the contamination of the broad Fe II would lead us to *underestimate* the broad emission line variability. To remove the Fe II emission from the $H\beta$ - $[O\ III]$ region as described in Chapter III was not deemed worthwhile considering the above discussion, the relatively low signal to noise ratios, and that a significant part of the Fe II $\lambda 4570$ complex, used to scale the total Fe II contribution in the red wing of $H\beta$, was usually not measurable (fell outside the spectral coverage). We found that the relative scaling between spectra, based upon the constancy of the $[O\ III]$ flux, was good to $\sim 8\%$ for 1E0357+107 and $\sim 4\%$ for the remainder of the QSOs observed. That is, if the relative scale factor differed from that chosen by more than this amount, one could begin to detect residual $[O\ III]$ emission.

The estimated flux measurement errors are 9.8% for 1E0357-007 and about 5.8% for the remainder of the objects. The flux measurement errors

for the IDS data were estimated to be 8-10%. The statistical significance of any variation in the broad emission line or continuum was determined through a "t-test" with the errors assumed to be known. Flux variations that differed statistically at the 95% level or better were deemed "significant" variations; variations at lower levels of confidence were "marginal" and not believed. Those variations at better than the 99% confidence level were deemed "highly significant". However, it is the highly significant flux variations that we are especially interested in to confirm the short timescale broad line flux variability in HLAGN. This type of variation would also be required in future studies to determine the sizes of the BLRs in QSOs.

To set and measure the continuum a straight line was drawn between about 4750Å and 5100Å; these endpoints are generally emission line free. So as to not introduce more noise and sources of error, the two narrow lines of [O III] and the broad Fe II were not subtracted from the region near the red wing of H β . Instead, all broad H β line fluxes were consistently measured between 4750Å and 4950Å, just blueward of the narrow line [O III] λ 4959. This measurement includes the constant but very weak narrow-line H β , Fe II (m42) λ 4924 and possibly other multiplets of Fe II (Joly 1988). Permitted Fe II is known to vary with the broad emission lines, but the optical multiplets may vary with a lower amplitude (Wamsteker et al. 1990). If the nearby Fe II does vary with a lower amplitude, then this would again result in an *underestimate* of broad H β variability. However, the weakness of the Fe II in all of the spectra guarantees that λ 4924 did not confuse the measurement of broad H β . Missing from this measurement are the extreme red wings of

H β , containing very little ($\sim 7\%$) of the total line flux.

B. Individual Results

Of the 8 QSOs observed, 2 showed evidence for significant broad emission line variability (PG0026+129, 1E0357+107) and 1 varied at the highly significant level (1E0514-001). Two others (0833+446 and PG0052+251) varied marginally. Not even continuum variations were observed in the other QSOs. Table 2 outlines for the variable QSOs the (rest frame) broad emission line and continuum fluxes and equivalent widths, and lists the t-statistic (with the errors known) for continuum and line variations. The time intervals between observations were binned into the 2 groups discussed earlier: 2-3 months and 9-12 months. In addition, multiple CCD observations and some IDS data allowed us to check for variability in a few objects on timescales of 2-4 weeks and 8-9 years. The binned time interval between observations, the number of QSOs observed in the binned time interval, the number of pairs of observations per time interval, the number of pairs that showed broad line variability during a given time interval, and which QSOs were observed to vary on that timescale are shown in columns 1-5 of Table 3, respectively. An observation pair has been defined to mean 2 consecutive observations. Figures 1-5 show examples of (rest frame) spectra of the non-varying, or marginally varying, QSOs and their differences, while Figures 6-8 show the same for the 3 significantly varying QSOs. CCD observations that were compared with the IDS data were smoothed to the IDS resolution in each case. Below we discuss the individual results for the observed QSOs.

Table 2
Rest Frame Continuum and H β Fluxes for the Varying QSOs

QSO	Julian Date (2440000+)	F_{λ} ¹ (5000Å)	$F(H\beta)$ ²	W_{λ} (Å)	"t" Statistic ³
(1)	(2)	(3)	(4)	(5)	(6)
PG0026+129	4553	3.59±0.29	2.27±0.18	60.0	0.946, 0.867 0.702, 0.957 0.766, 0.959
	7413	2.99±0.24	2.00±0.16	64.8	
	7778	3.15±0.18	1.68±0.10	50.1	
	7848	2.97±0.17	1.93±0.11	63.0	
1E0357+107	7572	1.23±0.12	1.30±0.13	105.1	0.995, 0.950
	7848	1.75±0.17	1.64±0.16	90.6	
1E0514-001	7573	2.61±0.15	2.28±0.13	81.6	0.997, 0.995
	7849	3.27±0.19	2.82±0.16	79.6	

¹: in units of 10^{-15} ergs s⁻¹ cm⁻² Å⁻¹

²: in units of 10^{-13} ergs s⁻¹ cm⁻²

³: for continuum and line variations, respectively.

Table 3

The Distribution of QSO Observations and Broad Line Variability

t_{Bin}	Number of QSOs observed per bin	Number of Pairs of Observations	Number of Pairs that Varied	Which QSOs Varied
(1)	(2)	(3)	(4)	(5)
2 - 4 weeks	2	3	0	-
2 - 3 months	5	5	0-1	PG0026+129
9 - 12 months	5	5	1-3	1E0514-001 1E0357+107 PG0026+129
8 - 9 years	2	2	0	-

Total Number of QSOs Observed: 8

Figure 1. The two observations of H β PG0052+251 (JD 2447778 light, JD 2447848 heavy) and their difference (lower heavy = JD 2447848 - JD 2447778). All difference spectra in the figures that follow are the later date minus the earlier.

Figure 2. The same as Figure 1 for PG0157+001 (= Mrk 1014) (JD 2447788 light, JD 2447848 heavy). Note the strongly blue asymmetric [O III] lines.

Figure 3. The same as Figure 1 for NAB0205+024 (JD 2447783 light, JD2447847 heavy).

Figure 4. The same as Figure 1 for 0833+446 (= US1329) (mean of JD 2447572,7560,7534 light, JD 2447849 heavy).

Figure 5. The same as Figure 1 for PG0906+484 (mean of JD 2447573,7572,7571 light, JD 2447848 heavy).

Figure 6. The observational pair of PG0026+1219 (JD 2447778 light, JD2447848 heavy) and their difference. A significant increase in the broad emission line flux occurred over the time interval $\Delta t = 70$ days.

Figure 7. The two observations of 1E0357+107 (JD 2447572 light, JD 2447573 heavy) and their difference. The continuum underwent a highly significant variation; the broad emission line varied significantly over $\Delta t = 276$ days.

Figure 8. The observational pair of 1E0514-001 (mean of JD 2447573,7560 light, JD 2447849 heavy) and their difference. Both the broad H β and continuum fluxes underwent highly significant variations over the timespan $\Delta t = 276$ days.

1. PG0052+251

Figure 1 shows variations in the broad H β flux at the 8% level and in the continuum at the 7% level over the time interval of $\Delta t = 69$ days. The excess emission in 2447778 near 4850Å and 4876Å (restframe) are apparently not spurious, as they appear in every exposure for that night. The nearest night sky line lies 21Å blueward of the blue excess, and we do not believe them to be artifacts of the division by the flat field. However, whether these represent a true profile variation and thus a change in the line flux is difficult to say. The broad emission line and continuum variations are significant at the 85% and 78% confidence levels, respectively, and are thus taken to be marginal detections of variability.

2. PG0157+001 (= Mrk 1014)

The continuum and broad line flux levels are the same in both observations, separated by 60 days, the only observational pair for this QSO (see Figure 2). Note in Figure 2 the [O III] profiles have a fairly strong blue asymmetry. The "blue" feature is real as it appears in both spectra, and it is almost certainly [O III] since the blue asymmetry has the correct flux ratio of 3:1. Blue asymmetries in narrow lines are common in Seyfert and radio galaxies (Heckman *et al.* 1981). Direct imaging (Heckman *et al.* 1984; MacKenty and Stockton 1984; Smith *et al.* 1986; Stockman and MacKenty 1987) has shown a large (~ 90 kpc) extended spiral-like continuum emission region surrounding the nucleus, but little if any extended [O III]. In any case the ratio of the blue to the main component remained constant between the two spectra. We are

therefore confident that the secondary (blue) component did not affect our ability to accurately place both observations on the same flux scale.

3. NAB0205+024

No continuum or broad emission line variations were detected between JD 2447783 and JD 2447847 (see Figure 3). Another observation made with the IDS taken ~ 9 years prior is identical to the above two spectra.

4. 0833+446 (= US1329)

Observations separated by 26 days (JD 2447534 and JD 2447560) and 12 days (2447560 and 2447572) show no variation and are all identical. A mean of these 3 spectra was then compared to one taken 277 days later (JD 2447849). Figure 4 shows a -11% change in the broad H β flux and +11.6% change in the continuum over the latter period. These variations are significant at the 92.5% and 90.0% confidence levels, respectively, and thus were considered to be marginal.

5. PG0906+484

Those observations of this QSO taken on JD 2447571, 2447572, and 2447573 were averaged and compared to that taken on JD 2447848 (Δt = 275 days), and the latter was then compared to 2447915 (Δt = 67 days). No variations in continuum or broad emission line fluxes were detectable in either case (see Figure 5).

6. PG0026+129

Significant variations in both the broad emission line and the continuum on short timescales have, apparently, been observed before for

this object: 10 months (Zheng *et al.* 1987) and 12 months, based on broad $H\beta/[O\ III]$ flux ratio comparisons between data from Peterson, Foltz, and Byard (1981) and Shuder (1984). Table 2 and Figure 6 show that the broad $H\beta$ flux decreased (-16%) between JD 2447413 and JD 2447778 (365 days) and then returned (+15%) to the JD 2447413 level by JD 2447848 (70 days). Both variations were at the $\sim 96\%$ confidence level, i.e., significant variations. The night sky line of $[O\ I]\lambda 5577$ falls on the red side of the core of $H\beta$ (near $4872\text{\AA}$). However, Figure 6 shows that most of the variation occurred, or at least most of the residual flux lies, blueward of where the sky line falls. It is clear that the residual broad emission flux in Figure 6 is not due to imperfect removal of this night sky line in any of the spectra. The continuum was essentially at the same level during all 3 observations. If the broad emission line variation is real, then the continuum must have changed twice (decrease and then increase) sometime in the past, *perhaps* between JD 2447413 and JD 2447778. These short timescale variations are important if they are indeed real; a 70 day variation of the broad emission line flux would be one of the shortest ever measured for this luminosity class. A significant continuum change (-17%) and a statistically insignificant broad line change (-13%) also occurred over the long time interval between JD 2444553 and JD 2447413. The broad line change is significant at only the 86.7% confidence level and hence not very believable.

7. 1E0357+107

This QSO has not been observed to the extent of PG0026+129. There have been no previous reports of continuum or broad emission line flux variations in this object. However, we have detected a highly significant (at the 99.5% confidence level) change in the continuum at 5000Å (+44%) and a significant (at the 95% confidence level) change in the broad H β flux (+26%) between JD 2447572 and JD 2447848 (276 days) (Refer to Table 2 and Figure 7). No night sky lines of any significance fall anywhere near the H β region.

8. 1E0514-001

There are no previous reports of broad emission line variability in this QSO. The first two observations, JD 2447560 and JD 2447573 ($\Delta t = 13$ days) were identical, and averaged together. However, Table 2 and Figure 8 show that this QSO underwent highly significant broad H β and continuum variations (+24% and +25%, respectively) between a 276 day period (JD 2447573 and JD 2447849). The changes in the continuum and broad emission line are significant at the 99.5% and 99.7% confidence levels, respectively. The night sky lines of [O I] $\lambda\lambda$ 6300,6363 fall near 4876Å and 4925Å, respectively. However, there is no indication of over- or undersubtraction of these lines in any of the spectra, and indeed the bulk of the residual flux lies blueward of these positions, and is as broad as either of the parent broad H β profiles. He II λ 4686 and/or the Bowen fluorescence line N III λ 4640 also increased in flux over the time interval. In this instance, we have no doubt that variations occurred in both the continuum and the broad emission lines.

IV. Discussion and Summary

Even with a smaller sample and lower temporal coverage than originally planned, it is significant that this variability study found *definite* short timescale (< 1 year) broad emission line variations in at least 1 and possibly 3 radio quiet QSOs. We believe that this confirms that the broad emission lines of the higher luminosity AGN do vary and on relatively short timescales. However, short timescale variability is certainly not rampant among the radio quiet QSOs as only one highly significant broad emission line change is detected. The sample of 6 OVQs observed by Perez, Penston, and Moles (1989) appear to be more variable than the radio quiet QSOs selected here, for example. However, they suggest that an ionizing continuum beamed near our line of sight could account for the short timescale broad emission line variability observed in some radio loud QSOs and perhaps all AGN. Although there is no evidence for beamed continua in the BLRs of *radio quiet* QSOs, such as those selected in our study, this possibility must be considered. Further studies are needed to better establish what temporal sampling would be sufficient in future monitoring programs to determine the transfer functions of the BLRs (see Blandford and McKee 1982) in the high luminosity AGN.

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CHAPTER III
THE BROAD EMISSION LINE PROFILES AND PROFILE VARIABILITY
OF THE SEYFERT 1 GALAXY ARAKELIAN 120

I. Introduction

Since its discovery and identification as luminous Seyfert 1 galaxy (Arakelian 1975, Osterbrock and Phillips 1977), Arakelian (Akn) 120 has been observed to be highly variable in its continuum and broad permitted lines (Lyutyi 1976; Kollatschny *et al.* 1981; Schulz and Rafanelli 1981; Peterson *et al.* 1983, 1985; Peterson, Korista, and Wagner 1989; hereafter Paper I), and in the profiles of the broad permitted lines (Foltz *et al.* 1981; Capriotti, Foltz, and Peterson 1982). Early attempts of monitoring the continuum and broad emission line fluxes in Akn 120 found surprisingly small lags between the two (Peterson *et al.* 1983, 1985). They found that the latter lags the former by 30-50 days, indicating a correspondingly small broad line region (BLR) in this Seyfert galaxy. A cross-correlation analysis of the continuum and broad emission line fluxes for the entire Ohio State University Image Dissector Scanner (OSU IDS) Akn 120 database (discussed below) found the primary peak in the cross-correlation function to lie near 0 days, due to correlated errors in the $[O\ III]\lambda 5007$, continuum and broad $H\beta$ flux measurements. However, the function was highly asymmetric towards

positive lags, and a secondary peak had a corresponding lag of 51 ± 12 days (Paper I). Peterson and Gaskell (1990) found through the same analysis of the *IUE* ultraviolet data a lag of 39 ± 14 days. However, until the transfer function is found, we cannot investigate the distribution of the line emitting gas in the BLR via this method.

The structure of the BLR may also be investigated through the analysis of the broad emission line profiles. Recent profile analyses of NGC 5548 (Peterson 1987; Peterson, Korista, and Cota 1987; Peterson et al. 1990a; Wamsteker et al. 1990) have all pointed to a multicomponent BLR for this Seyfert galaxy. With its very asymmetric, "lumpy", and multi peaked Balmer line profiles, this is indicated for Akn 120 as well. Although the broad line profiles in many broad line active galaxies are smooth, perhaps slightly asymmetric, and triangular looking (e.g., Mrk 509), the more complex appearing broad line profiles in these two Seyfert galaxies are by no means unique; NGC 3227, Fairall 9, Mrk 290, Mrk 279, Mrk 876 are other examples. Here we present an analysis of the broad emission line profiles (for mainly $H\beta$ $\lambda 4861$) and their variability for the entire OSU IDS Akn 120 database and some 20 recent CCD spectra of Akn 120, in an attempt to place some constraints on the structure of the broad line emitting region in this Seyfert galaxy.

Section II describes the Akn 120 database, including the recent CCD data. Section III is an analysis of the broad emission line profiles, where we remove the contribution of 3 multiplets of Fe II to the $H\beta$ profile, and then the methods of constructing difference profiles and profile fitting are employed in an attempt to isolate the "components". The results are summarized and future work is suggested in Section I.

II. The Arakelian 120 Database

Over the past 10 years well over 100 spectroscopic observations of $H\beta$ $\lambda 4861$ in Akn 120 were made by various astronomers and graduate students (the author included) of the Ohio State University on the 1.8m Perkins telescope of the Ohio State University and Ohio Wesleyan University at the Lowell Observatory. About 3/4 of these were obtained with the Ohio State University Image Dissector Scanner (IDS) (see Byard *et al.* 1981). These data were acquired and reduced as described by Peterson (1987); the $H\beta$ and continuum fluxes are given in Paper I. Typical signal to noise ratios (S/N) and spectral resolution acquired were 40-50 and 9-12Å, respectively. The spectral range covered by the IDS was typically 4000Å-6000Å, in the rest frame of Akn 120 ($z = 0.03248$). The temporal coverage was fairly good; the median interval between observations was 20 days, although the sampling was very uneven. The remaining 1/4 of the database were obtained since 1988 December with the Ohio State University CCD spectrograph. Generally, a 350 lines per millimeter grating and a 5 arcsecond slit were used, which resulted in a spectral resolution of about 9Å. The spectral range covered was typically 4400Å-5500Å, in the rest frame of Akn 120. From here on these will be designated as the higher dispersion data; on four occasions (JD 2447777, 2447796, 2447809, and 2447823) a lower dispersion grating was used with a spectral resolution of about 13.5Å. Signal to noise ratios in the CCD observations ranged from ~ 80-110 for typical exposure times of 1-2 hours. Chapter II described some of the basic data acquisition and reduction procedures followed. Column (1) of Table 4 lists the higher dispersion CCD observations of Akn 120, from JD 2447524 (1989

December) through JD 2447949 (1990 February). The mean interval between observations between JD 2447777 and JD 2447915 was 8.5 days, and the sampling much more regular than the IDS dataset.

All of the $H\beta$ data have been put on a common flux scale by scaling them to the same flux in narrow $[O\ III]\lambda 5007$ which we assume to be constant over the timescales considered here (see Paper I). This line is by far the strongest narrow line in the spectrum and for this reason most of the spectra are centered near $H\beta\ \lambda 4861$. However, because of the strong, broad Fe II contribution and the weakness of the narrow lines in this Seyfert galaxy, in particular $[O\ III]$, the flux measurement of $[O\ III]\lambda 5007$ is the largest contributor to the uncertainty (see Paper I; Baribaud and Alloin 1990). The narrow line region in Akn 120 is spatially unresolved on the 1 arcsecond scale (Whittle 1981), thus with the large apertures used aperture effects are expected to be unimportant.

In addition to the $H\beta$ data, nearly 2 dozen, mainly IDS, $H\alpha\ \lambda 6563$ spectra were also taken. No narrow lines of sufficient strength for use in variability studies are present near $H\alpha$. This made it difficult to place the $H\alpha$ spectra on the same flux and wavelength scales. Some of the $H\alpha$ scans were simultaneous with $H\beta$. However, these were usually of lower quality since in this case the Balmer lines lay near the ends of the spectra, where the sensitivity and spectral resolution of the IDS decreased significantly.

Table 4
CCD Observations of Akn 120

Julian Date (2440000+)	$F_{\lambda}(5000\text{\AA})^{1,3,4}$	$F(H\beta)^{2,3,4}$
(1)	(2)	(3)
7524	17.63 ± 0.88	18.29 ± 0.91
7559	18.83 ± 0.94	19.04 ± 0.95
7582	19.40 ± 0.97	20.10 ± 1.01
7589	18.95 ± 1.52	20.07 ± 1.61
7783	19.58 ± 0.98	17.01 ± 0.85
7788	19.60 ± 0.98	17.09 ± 0.85
7816	19.29 ± 1.56	17.52 ± 1.40
7831	20.15 ± 1.01	19.28 ± 0.96
7837	19.99 ± 1.60	19.06 ± 1.52
7846	19.19 ± 0.96	20.07 ± 1.00
7852	19.91 ± 1.00	19.71 ± 0.99
7857	19.43 ± 0.97	18.79 ± 0.94
7884	18.47 ± 0.92	19.76 ± 0.99
7891	19.07 ± 0.95	19.85 ± 0.99
7900	17.63 ± 0.88	19.43 ± 0.97
7907	17.63 ± 0.88	19.65 ± 0.98
7915	18.83 ± 0.94	20.49 ± 1.02
7929	19.31 ± 1.54	19.46 ± 1.56
7949	19.43 ± 0.97	19.82 ± 0.99

¹: in units of 10^{-15} ergs cm^{-2} s^{-1} $\text{\AA}^{-1}$.

²: in units of 10^{-13} ergs cm^{-2} s^{-1} , includes the Fe II shelf.

³: all fluxes measured in the rest frame of Akn 120.

⁴: dereddened for an $E_{B-V} = 0.12$ mag.

Most of the remaining H α scans had some wavelength overlap with an H β scan, taken typically 1-3 days apart, and an attempt was made to match the correctly scaled contemporaneous H β scan in the overlap region. However, for the reasons given above and because the flux calibration was generally less reliable at the ends of the IDS scans, the correct scaling of the H α spectra was not known very well in many cases. For all of these reasons and due to the smaller number of H α observations we restrict most of our analysis to the broad emission of H β .

Very little stellar contamination to the spectrum is expected (Edelson and Malkan 1986) and no attempt was made to remove it. The fact that the stellar contribution is small in Akn 120 is especially important in the analysis of the broad emission line profiles (Crenshaw and Peterson 1985). We adopted the correction for Galactic reddening from Paper I, as determined by Alloin, Boisson, and Pelat (1989), i.e., $E_{B-V} = 0.12$. All of the data have been put into the restframe of the narrow emission lines of [O III], $z = 0.03248$ (Osterbrock and Phillips 1977). Measurements of the continuum and H β fluxes for the higher dispersion CCD data are tabulated in columns (2) and (3) of Table 4. The continuum was set and the flux in H β measured as in Paper I (see also Peterson *et al.* 1985). However, note that this is not a true continuum level; both ends of the chosen continuum are contaminated with broad and variable Fe II (on both sides) and He II (near the blue wing) lines, as well as the wings of H β .

III. The Broad Emission Line Profiles

A. The $H\beta$ and $H\alpha$ Profiles: An Overview

Because of the relatively low signal to noise ratios and the inherent instabilities associated with an IDS, spectra of similar broad line profiles were combined when possible. A mean "profile state" was formed, weighting each spectrum by its signal to noise (all spectra very similar in profile belong to the same "profile state"). Very low quality data were rejected. In effect broad line profile features and/or variations were not believed unless observed in multiple spectra. Since no believable profile variations occurred during any single observing season (for the IDS data), generally September through March, the spectra were combined on this timescale. The IDS observations of $H\beta$ are given in Figures 9 and 10, four representative $H\beta$ profiles taken with the CCD spectrograph in Figure 11, and the approximately corresponding $H\alpha$ profiles are given in Figures 12 and 13. The last $H\alpha$ spectrum in Figure 13 JD 2447777, is a low resolution CCD observation, the rest are IDS scans. Note that an imperfect atmospheric B-band correction was applied to most of the $H\alpha$ spectra, affecting the profile in the region 6650Å-6670Å, in the rest frame of the narrow lines in Akn 120.

The Balmer emission line profiles in Akn 120 are very broad (FWHM $>5500 \text{ km s}^{-1}$), variable, and complex. Both $H\beta$ and $H\alpha$ profiles show a broad peak centered near line center (the central peak) and a second peak/plateau centered $\sim 2000 \text{ km s}^{-1}$ redward of this (the red peak).

Figure 9. The H β profile states for JD 2444615 (top left), JD 2445056 (top right), late 1982 through early 1983 (bottom left), and late 1983 through early 1984 (bottom right).

Figure 10. The H β profile states for late 1984 through early 1985 (top left), late 1985 through early 1986 (top right), late 1986 (bottom left), and early 1987 through late 1988 (bottom right).

Figure 11. Some representative CCD H β profiles: JD 2447524 (top left), JD 2447582 (top right), mean of JD 2447783 and JD 2447788 (bottom left), and JD 2447837 (bottom right).

Figure 12. $H\alpha$ profiles approximately corresponding to the $H\beta$ profiles in Figure 9: JD 2444615 (top left), JD 2445059 (top right), JD 2445266 (bottom left), and JD 2445704 (bottom right).

Figure 13. $H\alpha$ profiles approximately corresponding to the $H\beta$ profiles in Figures 10 and 11: JD 2446032 (top left), JD 2446482 (top right), JD 2446822 (bottom left), and JD 2447777 (bottom right).

In addition a few of the profile states in both $H\alpha$ and $H\beta$ show a blue shoulder located $\sim 2000 \text{ km s}^{-1}$ blueward of the central peak. This appears as a weak inflection our data and van Groningen's (1984) high resolution, high signal to noise spectrum from 1982 October and is especially obvious in our data observed since 1987 January. These "bumps" in the broad line profiles are not simply due to continuum excitation inhomogeneities, as was once suggested (Capriotti, Foltz, and Peterson 1982); they have persisted in the same place in velocity space for too long. Finally, the $H\alpha$ broad line profiles strongly hint of a very broad, $\sim 600\text{\AA}$ FWZI, base. Such a base cannot be observed in $H\beta$ as it is buried by Fe II and He II $\lambda 4686$ emission. At this point we loosely define a "component" to mean any "excess" (Balmer) broad line flux localized in velocity space. These broad line "components" will be discussed in more detail in a later section.

Also interesting is that the central peak *always* dominates in $H\alpha$, while $H\beta$ often appears to be double-peaked (i.e., both peaks of comparable intensities). In fact in early 1981 (see Figure 9) the red peak even exceeded the central peak. This double-peaked state in $H\beta$ was observed from 1981 January through 1984 March, and again in 1985 December through 1986 March (although the profiles in each period differed from one another). The apparent dissimilarity in the the relative strengths of the two peaks is not due to a steep Balmer decrement in the narrow emission which lies on top of the central peak. The narrow line emission is very weak in Akn 120, and the low excitation narrow lines are especially weak. The ratio of $[\text{O III}]\lambda 5007$ to narrow $H\beta$ is approximately 12:1.

Table 5
Estimated Relative Line Strengths of the
Stronger Narrow Lines

Narrow Line	Relative Flux ^{1,2}
(1)	(2)
[O III]λ4363	0.1
Hβ λ4861	0.083
[O III]λ4959	0.34
[O III]λ5007	1.00
[N II]λ6548	0.1
Hα λ6563	0.3
[N II]λ6584	0.3

¹: dereddend for an $E_{B-V} = 0.12$.

²: $F([O III]λ5007) = 1.35 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$, dereddened and in the rest frame of Akn 120.

Table 5 lists our estimates of the stronger narrow lines, in which we used $[O\ III]\lambda 5007$ as a template as described by Peterson (1987). Relatively large $[O\ III]\lambda 4363/\lambda 5007$ flux ratios, such as our measurement, are observed in other Seyferts in which the higher excitation narrow lines dominate (e.g. Fairall 9, III Zw 77). Most of the remaining narrow lines are the high excitation lines, including multiple lines of $[Fe\ VI]$ and $[Fe\ VII]$, $[Fe\ X]\lambda 6375$, possibly $[Fe\ XIV]\lambda 5304$, and $[Ca\ V]\lambda 5309$. Figure 14 shows $H\alpha$ from JD 2445763 cleaned of its narrow component and $[N\ II]\lambda\lambda 6548, 6583$; the central peak still dominates the $H\alpha$ profile, while $H\beta$ at this time was double-peaked. In addition the central peak is twice as broad as $[O\ III]$. As noted by Osterbrock and Phillips (1977), Foltz et al. (1981), and van Groningen (1984) the Balmer decrement of the red peak appears to be significantly flatter than that in the central peak and the rest of the profile. In addition, it is also possible that the broad emission comprising the central peak has a steeper Balmer decrement than the rest of the line. However, as we shall demonstrate in the next section, much of the apparent differences between the $H\alpha$ and $H\beta$ broad emission line profiles may be due to contamination of broad permitted Fe II within the $H\beta$ profile.

Figure 14. The broad H α profile corrected for the narrow lines of H α and [N II]: JD 2445763, top; JD 2446822, bottom.

B) The Origin of Anomalous $H\alpha/H\beta$ Ratio of the Red Peak

1. Possible Contribution of Fe II ($m25$, $m36$) to the $H\beta$ Profile

If this difference in the $H\alpha$ and $H\beta$ profiles is simply due to differing Balmer decrements across the profile (i.e., a red peak excess in $H\beta$), then the red peak ought to be stronger still, relative to the rest of the profile, in the higher order Balmer lines. This is not observed. In Figure 15 is $H\gamma$ $\lambda 4340$ after subtraction of $[O\ III]\lambda 4363$, which lies just $\sim 400\text{ km s}^{-1}$ blueward of the red peak ($+2000\text{ km s}^{-1}$), for an epoch in which the $H\beta$ profile appeared double-peaked and for one in which the $H\beta$ profile was dominated by the central peak. The same is shown for $H\delta$ $\lambda 4102$ also in Figure 15. Note that in both emission lines the central peak is dominant in both epochs, just as in $H\alpha$. Although the sensitivity of the IDS is declining in the blue, one can say that $H\alpha$, $H\gamma$, and $H\delta$ have qualitatively similar profiles at all times, and only $H\beta$ deviates with its double-peaked profile. Thus, it is reasonable to assume that some other (non-Balmer) emission is contributing to the red peak in $H\beta$.

The origin of the so-called *red shelf* which lies on the red wing of $H\beta$ and underneath the $[O\ III]$ lines has been investigated by numerous researchers, notably Foltz, Wilkes, and Peterson (1983) and Meyers and Peterson (1985) for Akn 120 (see also Crenshaw and Peterson 1986; Stirpe, van Groningen, and de Bruyn 1989, and van Groningen and de Bruyn 1989 for investigations into the *weaker* red shelves in other Seyfert galaxies). In all cases the researchers conclude that the red shelf cannot be entirely explained by the two lines in multiplet 42 of Fe II ($\lambda\lambda 4924, 5018$).

Figure 15. $H\delta$ and $H\gamma$, after correction for narrow $[O\ III]\lambda 4363$. At left is the mean spectrum from late 1983 through early 1984, at right is the mean spectrum from early 1987 through late 1988.

The most commonly invoked solution is to assume the existence of "broad" [O III] emitted in an "intermediate line region", or transition zone between the narrow and broad line regions. However, the Fe II multiplet 42 cannot, even with the addition of broad [O III], account for the red peak excess in the H β profile.

The optical Fe II emission in Akn 120 is very strong. Thus, another possibility is some other yet unaccounted for Fe II emission line. Calculations by Joly (1988) found that for strong optical Fe II emitters, multiplets 25 and 36 should be large contributors to the red side of the H β profile; 7 lines in these two multiplets span from 4856Å to 5037Å. *In fact Fe II m36 λ 4894 lies directly beneath the red peak in H β .* In addition multiplet 35 emission should also be significant, which can complicate any estimates of the strength of the multiplet 42 λ 5169 (which is generally used to estimate the strength of the two other lines of m42 that lie within the shelf).

2. The Red Shelf Fe II Template

Here we roughly construct an Fe II template, composed of multiplets 25, 36, and 42, which lie in the red shelf of H β . We use the following results from Joly (1988):

$$F(2/3 \text{ m42} + \text{m36} + 1/2 \text{ m25}) \approx 0.56F(\lambda 4570) \quad (3)$$

$$F(\text{m36}) \geq 0.5F(2/3 \text{ m42}), \quad (4)$$

where the fractions of multiplets refers to the fraction of the total number of lines within a particular multiplet that lie within the red shelf, and $F(\lambda 4570)$ is the flux of the Fe II complex that lies just

blueward of He II $\lambda 4686$.

Phillips (1978a) found that in the "narrow" broad line objects (in which the individual Fe II line are fairly well resolved from one another) the profiles of Fe II ought to be similar to that of the broadest component in the Balmer lines. The broad Balmer line profile in Akn 120 is complex, with a narrow central peak, a red peak, a blue shoulder, and possibly a very broad base. With the possibility that the broad Balmer line profiles are composed of multiple components, it was decided to keep the assumptions about the Fe II line profile as simple as possible. We thus assumed a Gaussian of FWHM of 4500 km s^{-1} , centered at the rest wavelength of each line. Although, we note that van Groningen (1984) perhaps found some evidence that the Fe II emission lies within the red peak and the blue shoulder components which he suggested to be the peaks of an accretion disk.

We further assumed that these Fe II lines are optically thick, which is a generally good assumption when optical Fe II is very strong. This means that the individual lines within each multiplet should be of nearly equal strength. We then chose a high quality IDS spectrum (the mean spectrum from JD 2446820 and JD 2446822) as a baseline spectrum from which to construct the Fe II template. A continuum was drawn as a straight line between $\sim 4190\text{\AA}$ and $5600\text{\AA}$. These two points probably lie closest to the true continuum which is indeterminable in entire spectral region of the scan due to the strong broad Balmer and Fe II lines. The placement of the underlying continuum is the largest contributor to the uncertainty in the template construction (which is why the higher quality, but lower spectral coverage, CCD data were not used to

construct the template). The flux in the Fe II ($\lambda 4570$) complex was then measured between $4440\text{\AA}$ and $4670\text{\AA}$, trying to exclude much of He II $\lambda 4686$. The flux in Fe II $\lambda 5169$ was then estimated, which set the flux in the other two $m42$ lines ($\lambda\lambda 4924, 5018$) which lie within the red shelf. Our estimate of the flux ratio of $m42$ $\lambda 5169$ to the $\lambda 5250$ complex was ~ 0.16 , comparable to the findings of Phillips (1978a) for some "narrow" broad line AGN in which many of the stronger individual lines could be measured. Using the two relationships given above, and assuming the equality in equation 2, the contributions of multiplets 25 and 36 were then determined.

Table 6
Model Fe II Template for the "Red Shelf"

Multiplet	Line (Å)	Relative Strength ^{1,2}
(1)	(2)	(3)
25	4855.5	0.32
	4871.1	0.32
	4991.1	0.32
	5000.7	0.32
36	4893.8	0.33
	4993.4	0.33
	5036.9	0.33
42	4923.9	1.00
	5018.4	1.00

¹: $0.56F(\text{Fe II } \lambda 4570) \approx 4.03 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$ for JD 2446822.

²: $F(\text{m42 } \lambda 5169)/F([\text{O III}] \lambda 5007) = 0.7$.

Figure 16. The mean spectrum from JD 2446820 and JD 2446822 (top, light) and the same with the $H\beta$ profile corrected for Fe II (top, heavy). The constructed Fe II template, including Fe II m42 $\lambda 5169$, is shown at the bottom. Note the probable presence of Si II $\lambda 5056$.

We note here that in addition to the aforementioned caveats, we are far from understanding how the extremely complex Fe II is produced in AGN. Table 6 lists the model relative line strengths of the 3 Fe II multiplets, and Figure 16 shows the Fe II template and JD 2446822 before and after subtraction of the Fe II template.

For the other spectra the template was scaled to the measured flux in the Fe II $\lambda 4570$ complex; implicit here is the assumption that the individual multiplets within the red shelf scale 1:1 with each other as the continuum varies. This may not always be true (Joly 1988). Figures 17-19 show the same as Figures 9-11 corrected for Fe II in the red shelf. Note that the resultant $H\beta$ profiles in most cases are dominated by the central peak, looking much as the other 3 Balmer lines do and more like each other. Comparing the two sets of spectra one sees that varying contributions of Fe II probably accounts for a significant fraction of the apparent variability of the broad line profile of $H\beta$. The Fe II emission and the red shelves were especially strong in early 1981 and again during the 1985-1986 observing season; a substantial red shelf remains in both after the correction is applied, especially in the 1981 data. It may be that our assumption that the profile of the Fe II shelf remains constant with the Fe II flux is not a particularly good one at large Fe II emissivities. The correction for Fe II in the red peak of $H\beta$ is therefore more uncertain for these spectra.

Figure 17. The same as Figure 9, corrected for the Fe II shelf. Note the probable presence of Si II $\lambda 5056$.

Figure 18. The same as Figure 10, corrected for the Fe II shelf. Note the probable presence of Si II $\lambda 5056$.

Figure 19. The same as Figure 11, corrected for the Fe II shelf. Note the probable presence of Si II $\lambda 5056$.

The largest recorded difference in the strengths of the red peaks in the Balmer lines was in the spectra published by Osterbrock and Phillips (1977). We believe that most of this difference can be attributed to contaminating Fe II. Although we do not rule out the possibility that, even after the correction for Fe II, the Balmer decrement ($H\alpha/H\beta$) in the red peak is flatter than in the rest of the line, it certainly is not as flat as was once thought (for these spectra and others). van Groningen (1984) found that the $H\beta/H\alpha$ ratio at the red peak was 1.3 times larger than at line center, and a smaller ratio closer to 1 near the blue shoulder. We find that the correction for Fe II in the red peak decreases this ratio here to a value closer to 1.

Some other important consequences result from this model. (1) With the contributions of the Fe II multiplets 25 and 36, substantial broad [O III] is no longer required; note how well the red wings of the corrected $H\beta$ and $H\alpha$ match in Figure 20. (2) The Fe II shelf accounts for 20-30% of the flux in the $H\beta$ + shelf (minus [O III]) region. (3) A weak, but nevertheless distinct, broad emission line became apparent near 5056Å in all of the corrected $H\beta$ spectra (see Figures 16-19). We identify this as Si II λ 5056. Another relatively strong Si II line should then also be present, Si II λ 5979. As this always lay near the end of a scan, we could not confirm its existence; however, van Groningen (1984) found some evidence for its presence in the red wing of He I λ 5876.

Figure 20. $H\beta$, JD 2447582, continuum-subtracted and corrected for the narrow lines and the Fe II shelf (heavy), and $H\alpha$, JD 2446822 (same profile state as $H\beta$), corrected for the narrow lines, shifted into the velocity space of $H\beta$, and scaled such that the blue cores of the profiles match (light). Note how well the red sides of the profiles match after the correction for Fe II.

This is important, as the presence of these Si II lines is indicative that resonance fluorescence is an important emission mechanism for Fe II (see Phillips 1978b), at least in Akn 120 (just which emission mechanisms are important is still a source of controversy). If this is the case then multiplets 43, 55 and some lines in m49 ought to be weak relative to multiplets 27, 28, and 42 (Phillips 1978b). We cannot say much about multiplets 43 and 49, as they lie in confused regions of the spectrum, but multiplet 55 ($\lambda 5433, \lambda 5535, \lambda 5591$) certainly is very weak (see Figures 16-19). (4) None of the model templates of the Fe II shelf were flat-topped, but were double-peaked, the narrower peak (width about $50\text{\AA}$) lay centered near $5009\text{\AA}$. This peak typically added $\sim 5\%$ more flux to the $[\text{O III}]\lambda 5007$ measurement, made prior to subtracting the Fe II shelf, and perhaps more in those spectra where the shelf was especially strong. A variable and complex Fe II contribution and could therefore affect the internal flux calibration on this level. However, we caution that this particular result is extremely model dependent, as we do not know the true Fe II emission line profile, their position in velocity space, or how the individual multiplets of Fe II within the shelf react to changes in the continuum. This problem may be alleviated somewhat by taking difference spectra of high S/N ratio, better than $9\text{\AA}$ resolution, data and scaling until the narrow line $[\text{O III}]$ disappears in the difference. In any case we expect this to be less of a problem in higher resolution data.

These results are not strongly dependent upon our estimate of the strength of the m42 lines; tests were made with a reasonable range of strengths and all results were qualitatively similar. Despite the

numerous uncertainties in the construction of the Fe II template, we believe that it is a good first order correction to the H β broad emission line profile.

C. Profile Variability in Akn 120

We will concentrate our analysis on the profile variability of H β λ 4861, for which we have the largest and most reliable database.

1. An Overview

The median interval between IDS observations of H β was 20 days, and large variations in the broad emission line and continuum fluxes were also observed over the 7 years of IDS observations (see Paper I). However, neither of these were of much use in a profile analysis as *all 3 significant changes in broad emission line profile occurred during the 5 month or so period in which Akn 120 is too close to the Sun, or in the large gaps in the temporal coverage (i.e., when we weren't looking).* These changes occurred between 1984 March and 1984 November, 1985 February and 1985 November, and 1986 March and 1986 September (see Figures 9 and 10). Two observations taken 1986 September and November (JD 2446675, JD 2446742) may have been profiles in transition between the 1985-86 profile state and that which apparently began in 1987 January (see Figure 10), but the quality of the data and lack of coverage during this time did not permit us to confirm this. The H β profile then remained approximately constant through 1989 March. Most or all of the apparent differences in profile between the 1987 January - 1988 September IDS mean profile state in Figure 10 and the CCD

observations between 1988 December and 1989 March (Figure 11) can be attributed to differences in signal to noise ratio and spectral resolution. A fourth significant profile change occurred during the CCD era between 1989 March and 1989 September, again during the unobservable period (see Figure 11).

While it was not possible with the IDS data to discern small changes in the broad line profiles, the significant profile variations in $H\beta$ that occurred between observing seasons certainly are real. These profile variations cannot be explained entirely by changes in the Fe II shelf, as we shall soon see. Although one would like to have data *while* the broad emission line profile is changing between profile states, it is significant that in spite of our temporal coverage (median observation interval: 20 days) *no profile variations were observed even when the lines and continuum varied, in many cases by 50% (see Paper I).* That is, changes in the broad line profile do not seem to be necessarily correlated with changes in the continuum on timescales longer than about a month. This is an indication of either that the dominant motions within the BLR are disordered or that the bulk of the Balmer line emitting gas is very near to the continuum source and we cannot resolve the variations (or both). Certainly the complex broad emission line profile argues against the dominance of disordered motion in the BLR. On the other hand, cross-correlation analyses of the continuum and $H\beta$ flux variations (Paper I; Peterson and Gaskell 1990) do indicate a small BLR in Akn 120. In addition there does not seem to be any correlation of profile state with either the strength of the continuum or of the emission line. All of the profile states presented here have been

through significant variations in both. The one exception to this is the extremely weak continuum and emission line flux data published by Osterbrock and Phillips (1977), in which the Balmer lines were completely dominated by the central peak (the FWHM was 4500 km s^{-1} compared to typically 5500 km s^{-1} for data since then), the blue shoulder was extremely weak if present at all, and the very broad base was apparently very weak (see Alloin, Boisson, and Pelat 1988); nothing like this has been observed since. Finally, the Balmer lines can remain in the same profile state for 1-2 years. Thus the major changes in the broad emission line profile presented here also cannot be due to excitation inhomogeneities due to a continuum pulse traveling through the BLR.

2. Difference Spectra: The "Components"

Construction of difference spectra is the most unbiased method of isolating variable broad emission line "components" because no assumptions are made. Here we present (mainly $H\beta$) difference spectra among the different profile states for the IDS and CCD data. Any differences in spectral resolution were corrected (smoothed with a Gaussian of appropriate width) prior to differencing.

a. $H\beta$

Figure 21 shows difference (IDS) spectra for the first 3 profile variations discussed above. No correction for the Fe II in the red shelf was made prior to the construction of the difference spectra, as the correction had little effect on the prominent features in the difference spectrum.

Figure 21. IDS H β difference spectra. Upper left: 1984-85 minus 1983-84; upper right: 1985-86 minus 1984-85; lower left: 1985-86 minus 1987-88; lower right: 1987-88 minus 1983-84.

However, significant effects might be encountered, especially near the red peak, if the Fe II shelf changes profile as a function of the continuum strength. Because of the relatively low S/N ratios and the spectral resolution in the "parent" IDS spectra, the amount of quantitative information that can be extracted from the difference spectra is rather limited. However, qualitatively we can state the following. First, between the 1983-84 and 1984-85 observing seasons a relatively narrow $\sim 2300 \text{ km s}^{-1}$ FWHM component, whose centroid lies somewhat blueward of line center, apparently increased in flux relative to the rest of the broad emission line. This localized residual flux may be associated with the central peak, although this is not entirely clear. Second, between the 1984-85 and 1985-86 observing seasons the two components located near $\pm 2000 \text{ km s}^{-1}$ apparently increased in flux relative to the remainder of the broad emission line. These relatively narrow ($\sim 2500\text{-}3000 \text{ km s}^{-1}$ FWHM) residuals are centered at approximately -2300 km s^{-1} and $+1800 \text{ km s}^{-1}$, respectively. However, it is not clear whether other changes in profile may have occurred as well. Third, between the 1985-86 and 1987 observing seasons the red peak apparently decreased substantially relative to the rest of the broad line profile. The position of the residual is somewhat redward of the previous measurements. This may be due to the anomalously large Fe II contribution to the red shelf in the 1985-86 spectra, as mentioned earlier. One can see a significant residual in the red shelf, which does not disappear even when our Fe II red shelf template correction is applied (this also applies to the difference spectrum discussed just above). The same red peak type residual is also seen in H γ $\lambda 4340$ and H δ

$\lambda 4102$. The residual appears to be relatively narrow (FWHM ~ 2500 - 3000 km s $^{-1}$), such as that measured in the previously discussed difference spectrum. The fourth difference spectrum in Figure 21 shows the relatively narrow blue shoulder and (probably) central peak components; the same two peaks are also present in the H γ and H δ residuals. We note that all of these components appear in differences among individual IDS spectra, but at lower signal to noise. Profile variations may have also occurred prior to late 1983 (see Figures 9 and 17); however, either the variations are not great enough or the number of observations are too small to say anything about these. The quality of the IDS data (S/N ratio, spectral resolution) is the limiting factor here.

Figures 22-26 demonstrate the power of data of significantly higher S/N (factor of 2) and slightly higher spectral resolution. Figure 22 shows the CCD data JD 2447582 and JD 2447524 (minus the Fe II shelves) and their difference. With S/N this high we can just begin to compare the difference profile to the parent profiles. Figure 23 shows the same difference spectrum corrected for Fe II and its continuum removed (the Fe II shelves and continua subtracted before differencing), scaled to the peak of the the H β profile of JD 2447582 (continuum-subtracted and corrected for the narrow lines and Fe II shelf). The difference profile is very similar to the parent profile, indicating that the profile did not change with the emission line and continuum fluxes. Another spectrum taken in between, JD 2447559, was in an intermediate flux state, while another taken on JD 2447589 was identical to JD 2447582.

Figure 22. CCD spectra and their difference. JD 2447582 (top, heavy), JD 2447524 (top, light), and their difference (JD 2447582 minus JD 2447524; bottom, heavy).

Figure 23. The continuum-subtracted H β profile from JD 2447582 corrected for the narrow lines and the Fe II shelf (heavy), and the difference spectrum in Figure 22 scaled to the peak of JD 2447582 (light). The profiles were corrected for the Fe II shelves and the continua were subtracted prior to differencing. The S/N ratios in both are high enough that comparisons between their profiles may be made.

Figure 24. JD 2447582 (top, heavy), the mean of JD 2447783 and JD 2447788 (top, light), and their difference (former minus the latter; bottom, heavy).

Figure 25. JD 2447837 (top, heavy), the mean of JD 2447783 and JD 2447788 (top, light), and their difference (former minus the latter; bottom, heavy).

Figure 26. JD 2447837 (top, heavy), JD 2447524 (top, light), and their difference (former minus the latter; bottom, heavy).

We believe that the broad line profile had been constant since 1987 January. Figure 24 illustrates the fourth major change in the broad emission line profile of $H\beta$, and apparently reveals another component. A broad (FWHM $\sim 3000 \text{ km s}^{-1}$), approximately Gaussian, component centered at about -875 km s^{-1} dropped in flux relative to the rest of the line profile between 1989 March and 1989 September (JD 2447589 - JD 2447783; i.e., when it was too close to the sun to observe). It is definitely a broader than and significantly blueward of the central peak. We call this the " $\lambda 4850$ " component. The flux difference within this component is merely 15% that of the entire broad $H\beta$ line flux, and yet it accounted for a great change in the broad line profile. There also appears to be significant excess emission near $+4000 \text{ km s}^{-1}$. Correcting for Fe II, using the constructed template, had no effect on this residual. The only known Fe II line that lies within this excess is m42 $\lambda 4924$; however, the other 2 lines of m42 (or any other multiplet, for that matter) did not vary as such. No other strong emission lines are known to lie within this excess; it is more than likely high velocity $H\beta$ emission.

Between JD 2447788 and JD 2447837 apparently both the red peak and the $\lambda 4850$ component have increased together, changing slightly the broad emission line profile of $H\beta$ (Figure 25). One can see that the intensity difference between the peaks of the central component and the blue shoulder changed between the two spectra. It is important to note here that the IDS data could not reveal these small changes in profile. A small, but believable $\sim 12\%$ change in $H\beta$ flux was detected, and apparently most of the variation occurred sometime during the 15 day

interval between JD 2447816 and JD 2447831. All subsequent $H\beta$ profiles through JD 2447949 are identical to JD 2447837. This may indicate that at least small profile changes may occur on very short timescales. In any case, the timescale for profile variability is certainly less than 5 months. In Figure 26 one can see that by JD 2447837 the $\lambda 4850$ component had returned to its strength of JD 2447524; however, since both this component and the red peak had increased together, a strong residual representing a net change in the red peak remains. Figure 26 also demonstrates that changes in the strength of the red peak are not in all cases due to changes in the Fe II shelf. The position and width of the residual red peak component in this CCD difference spectrum (approximately $+1800 \text{ km s}^{-1}$ and 2600 km s^{-1} FWHM) are very close to those seen in two IDS difference spectra.

b. $H\alpha$

Alloin, Boisson, and Pelat (1988; hereafter ABP) found that when a high and low state $H\alpha$ spectra of Akn 120 were differenced, a double peak residual resulted. This phenomenon has also been observed for NGC 5548 by Stirpe, de Bruyn, and van Groningen 1988. The two spectra they differenced were the extreme low-state spectrum from Osterbrock and Phillips (1977) and a high-state spectrum that closely corresponds to our data on JD 2444615. The positions and widths of the blue and red components identified by ABP correspond well to the blue shoulder and red peak components identified in the $H\beta$ difference spectra in this work. ABP interpreted this double peak as variable flux from an accretion disk. As we shall point out in Chapter IV, the difference

between a high and low state spectrum does not always result in a double-peaked residual. This was also pointed out for the case of NGC 5548 by Peterson *et al.* (1990a). In Figure 27 we show the difference between two H α spectra (JD 2445673 minus JD 2445647, 1983 Autumn) for Akn 120 for which it was possible to get a very good match to the H β scans (which were taken the next night, and a separate scan the same night, respectively). The difference in flux is approximately 30%. There is a broad peak, centered blueward of line center as defined by the narrow lines, lying very near to the central dip in Figure 3 in ABP. Within the limits set by the S/N, Figure 27 has a profile comparable to either of the parent profiles (after accounting for the narrow lines). In fact we find that the number of cases in which a double-peaked residual results is in a very small minority, most of which are associated with the Osterbrock and Phillips (1977) spectrum (kindly made available to us in digital form by Dr. D.E. Osterbrock). This is not surprising since the central core of the Balmer lines in this spectrum completely dominated the emission from the blue shoulder and the red peak.

Figure 27. Two H α profiles, JD 2445764 (top, heavy) and JD 2445647 (top, light), and their difference (bottom, heavy). The features near +4000 km s⁻¹ are spurious, and are due to imperfect atmospheric B-band correction.

ABP identified the emission "filling in" the classical double-peaked accretion disk profile as the constant narrow line component; this cannot be so because its width is ~ 4 -6 times that of the [O III] lines. De Robertis and Osterbrock (1984,1986) found in Seyfert 2 galaxies, and in Seyfert 1 galaxies in which the narrow Balmer component could be isolated, that the widths of the narrow Balmer lines are comparable to or slightly narrower than the [O III] $\lambda\lambda 4959, 5007$ lines. Baribaud and Alloin (1990), and Baribaud *et al.* (1990) clarify this position somewhat by identifying this component with emission coming from the Intermediate Line Region, mentioned earlier in connection with broad [O III] and the very high excitation forbidden lines. However, this too seems unreasonable, since the ratio of the Balmer line emission to the high excitation line emission would be much larger than expected from a region producing such high excitation lines. We think it more likely, considering the difference profiles we find in $H\beta$ (and $H\alpha$), that most or all of this emission is variable broad line emission. Its width and position are comparable to the so-called " $\lambda 4850$ " and central components identified in our difference spectra.

Finally, the $H\alpha$ difference spectrum in ABP revealed the presence of a very broad base. They modeled it with a Gaussian with a FWHM of $11,600 \text{ km s}^{-1}$; its rest position with respect to the narrow line region corresponds to $\sim 4875\text{\AA}$ for $H\beta$. We find a similar very broad residual for $H\beta$ as well. The Osterbrock and Phillips (1977) spectra must have had unusually weak wings, for we do not find in any other difference spectra such obvious very broad wings (the wings may be optically thin to the Lyman continuum and not expected to vary to the extent of the

line cores; see Chapter IV). Figure 28 shows that the wings of $H\alpha$ may be as broad as $\sim 30000 \text{ km s}^{-1}$ FWZI; van Groningen (1984) also finds evidence of such broad wings in his higher quality data.

Columns 1, 2, 5, and 6 in Table 7 summarize the approximate positions and widths of the broad emitting components within $H\beta$, as found through difference spectra. In column 3 we list those component positions found by van Groningen (1984) for comparison. As for the slight blueshift in the central peak found by van Groningen, we generally find a similar shift during the "double peak" profile states (as during his observation), but when the central peak dominates we find that it lies nearer to zero velocity relative to the NLR.

Table 7

Approximate Positions and Widths (FWHM) of the
"Components" Observed in the Difference Spectra

Position			FWHM ($\text{\AA}$)	
($\text{\AA}$)	$(\text{km s}^{-1})^a$		($\text{\AA}$)	(km s^{-1})
(1)	(2)	(3) ^b	(4)	(5)
4824	-2300	-1920	38.0	2360
4847	-875	-	48.5	3000
4860	~ 0	-230	25.0	1540
4875	+845	-	188.6	11600
4890	+1770	+1740	42.5	2600

^a: relative to the rest frame of $[\text{O III}]\lambda 5007$.

^b: from van Groningen (1984).

Figure 28. The base of the mean H α profile for the 1985-86 observing season (continuum-subtracted) showing the very broad wings. Weak [O I] λ 6300 and relatively strong [Fe X] λ 6375 lie on the blue wing.

3. Profile Fitting

Using Table 7 as a guide, an attempt was made to model the H β profiles from the CCD data. Recent attempts of deblending broad emission line components are (for NGC 4151) Clavel *et al.* (1987) and (for NGC 5548) Peterson, Korista, and Cota (1987) and Wamsteker *et al.* (1990). Our goal is to determine the *minimum number of components necessary* to describe the broad emission line profile. Just as with the difference spectra, mainly because of the relatively low S/N (~ 50), the IDS data were not of high enough quality to extract reliable quantitative information through profile fitting. Thus we modeled only the CCD data. We started with JD 2447582 and the mean of JD 2447783 and 2447788, between which the largest changes in broad line flux and profile occurred. In addition the S/N ratio in each exceeds 100, and they apparently have very similar continuum levels (differing unknown continuum levels can strongly affect the comparisons of the component fluxes between the fits). These data were first corrected for the narrow lines of H β and [O III] $\lambda\lambda$ 4959,5007, and for the Fe II shelf. We have no way of knowing a priori the shapes individual component profiles; we thus choose arbitrarily the convenient Gaussian profile. This already guarantees non-unique solutions. A non-linear least squares multiple Gaussian fitting routine which minimizes χ^2 was used. The Gaussian fitting routine was provided by Dr. R.H. Kaitchuck, and the χ^2 search programs are mainly due to Chandler (1965). The continuum was set by a straight line between $\sim 5100\text{\AA}$ and $\sim 5500\text{\AA}$ and extrapolated under H β , which is probably much closer to the true continuum than that used to determine continuum and H β fluxes in Table 4. In all models the

approximated continuum was then held fixed, along with the line width and position for the very broad base, due to the difficulty the program had in identifying it otherwise. This was on account of the broad Fe II and He II lines that effectively bury most the very broad wings of H β (which are seen in H α). The line strengths were always free to vary. Finally, all those models in which the line positions and/or widths varied by more than one resolution element (9Å), between the fits of the two epochs, would be rejected. As we have stated above the positions of (at least 3) the components are known to be persistent in time, and we don't expect the component widths to vary.

Initially, three line fitting experiments were done, and the results of each are tabulated in Table 8 and illustrated in Figures 29-36. In all experiments 5 components were initially assumed; i.e., those 5 components found in the difference spectra served as our guide. In the first experiment the line positions were chosen from Table 7 and held fixed, the line widths were allowed to float in the fit to JD 2447582 and then fixed to those values for the fit to JD 2447788. The component widths found from the fit to JD 2447582 are comparable to those found in the difference spectra (compare Tables 7 and 8). Figures 29-36 show the two corrected spectra, their fits, and the differences between the two (real and fitted spectra). The primary peak in the difference spectrum is fitted well and the secondary peak is represented in the difference of the fitted spectra (we will call this the model difference spectrum).

In the second experiment the widths of the components for JD 2447788 were not held fixed. Table 8 shows that the component fluxes between the first two models of JD 2447788 did not vary significantly and the

component positions and widths varied by less than a spectral resolution element (9Å). Figures 32 and 33 show the fit to H β is a bit better and the model difference spectrum is fitted better, especially the secondary peak. Although the exact values of the component fluxes within Table 8 are not to be taken too seriously, the trends may be considered. The first 2 models indicate that the difference spectrum is due to a decreases in the λ 4850 and the very broad components, while the red peak and blue shoulder increased. That the components could be out of phase is not surprising considering the time that separates the two spectra.

In the third experiment the line positions and widths (except for the very broad component) were free parameters for both epochs. Here the least amount of information is assumed. The results were interesting (see Table 8 and Figures 34-36). The blue shoulder, the central peak, and the red peak components were all identified by the fit, as expected (the very broad base was fixed, as described earlier). However, to within the limits set by our spectral resolution (9Å) and our temporal coverage of the change in profile, the fits to the data and the difference spectrum between the fits are just as good as fits of the the first two experiments *without the need of the λ 4850 component*. Thus, it is very possible that the difference spectrum between JD 2447582 and JD 2447788 may not at all represent a separate emitting component but is an artifact of the variations of the remaining four. The results of the third experiment (Table 8) show that the residual may be due to 3, and perhaps all 4, components decreasing differentially. When experiment 2 was repeated for the line positions found for the fit

to JD 2447582 in experiment 3, the central peak decreased by $\sim 40\%$. It is certain that at least 2 localized regions in velocity space must vary with respect to one another if a change of profile is to occur. The profile is too complicated to be fit with just 3 Gaussians. In fact if the component profiles do not deviate greatly from Gaussian, then a minimum of 4 broad emission line "components" are required to compose the broad Balmer profiles, and we have shown that the fifth component may not be necessary.

Finally, we note that upon comparing the component line positions in Table 8 between experiments 1 and 3 one can see that of the three easily discernible components (blue shoulder, central peak, and red peak) the position of the blue shoulder is the most uncertain, as expected. All we can state at this point is that it lies somewhere between the extremes, -1700 and -2300 km s^{-1} relative to the narrow line region.

Table 8
Gaussian Fits to the Broad H β Profile

Experiment	Julian Date (2440000+)	Position ¹ (Å)	FWHM ¹ (Å)	Flux ²
1	7582	4824.0 (F)	38.98	1.68
		4847.1 (F)	46.62	4.53
		4860.0 (F)	17.83	0.78
		4875.0 (F)	188.60 (F)	7.31
		4890.0 (F)	42.96	4.37
	7788	" (F)	" (F)	2.01
				2.97
				0.82
				5.23
				4.68
	7582	Same	Same	Same
2	7582	Same	Same	Same
	7788	Same	45.08	2.10
			49.28	3.00
			19.66	0.99
			188.60 (F)	5.58
			37.75	4.16
	7582	4834.82	44.89	4.94
		4858.27	19.66	1.17
		4875.0 (F)	188.60 (F)	7.06
		4886.19	39.89	4.63
3	7582	4834.82	44.89	4.94
		4858.27	19.66	1.17
		4875.0 (F)	188.60 (F)	7.06
		4886.19	39.89	4.63
	7788	4833.74	50.22	4.52
		4859.01	20.22	1.18
		4875.0 (F)	188.60 (F)	5.40
		4888.52	39.89	4.63

Continuum held fixed in all cases.

¹: (F) refers to the value being fixed during the fit.

²: fluxes in units of 10^{-13} ergs cm⁻² s⁻¹.

Figure 29. JD 2447582 corrected for narrow and Fe II shelf emission (heavy) and its fit from experiment 1 (light).

Figure 30. JD 2447788 corrected for narrow and Fe II shelf emission (heavy) and its fit from experiment 1 (light).

Figure 31. The difference spectrum (JD 2447582 - JD 2447788) (heavy) and the difference between the respective fits (light).

Figure 32. The same as Figure 30 for experiment 2.

Figure 33. The same as Figure 31 for experiment 2.

Figure 34. The same as Figure 29 for experiment 3.

Figure 35. The same as Figure 30 for experiment 3.

Figure 36. The same as Figure 31 for experiment 3.

This exercise has demonstrated the following: (1) Not only are high signal to noise ratios needed (>100) (as demonstrated by the superiority of the CCD over the IDS data), but higher resolution (by least a factor of 2) is also needed to disentangle the components. (2) One has to be *extremely careful* in interpreting difference spectra, and high temporal resolution is required in order to decipher how the broad emission line profile is truly changing as a function of the line of sight velocity, time, and the variable continuum. The limited usefulness of "mean" profile states (i.e., the IDS data) also becomes apparent.

To lend more credence to the components found through profile fitting one needs to show that the same components can account for all other observed profile states. Unfortunately, only one significant variation in profile has occurred since we began observing Akn 120 with the CCD spectrograph. Even when this can be done, however, one must be very careful in interpreting the model component fluxes. This is primarily due to the fact that we cannot define a continuum, or even a consistent pseudocontinuum in this object, when the continuum varies, for this region of the spectrum. Greater spectral coverage might help somewhat. Additionally, if the "components" are not Gaussians, which they are probably not, the predicted component strengths and widths (and number!) can be greatly misleading. For both of these reasons and the results of the above 3 experiments, we believe that modeling the broad emission line profiles through profile fitting suffers from a severe uniqueness problem. The results of such an analysis should be treated with great caution.

D. Other Broad Emission Lines

Here we discuss qualitatively the profiles of other prominent broad emission lines in the spectrum of Akn 120. Figures 37-41 show the profiles of He I $\lambda 5876$ and mean spectra of the stronger ultraviolet lines as observed by *IUE*. At the S/N and spectral resolution of the *IUE* data, no significant profile variations were apparent.

Much of the dip in He I $\lambda 5876$ near $+1000 \text{ km s}^{-1}$ (see Figure 37) is due to Na I D $\lambda\lambda 5890, 5896$ galactic absorption intrinsic to Akn 120. Otherwise its profile seems to be quite comparable to that of the Balmer lines, showing evidence for the same components discussed in the latter. Although heavily blended by Fe II we can state that the red peak component is either very weak or absent in He II $\lambda 4686$. The blue side of the line is completely blended by Fe II, so little can be said about its profile here. As one can see in Figures 38 and 39 the weakness of the red peak component is also evident in the high excitation UV lines of Ly α $\lambda 1216$ and C IV $\lambda 1549$ (as also noted by van Groningen 1984, and ABP). Note that much of the emission near $+6000 \text{ km s}^{-1}$ in Ly α is due to broad N V $\lambda 1240$. Very broad wings in C IV are also apparently present. Although it is difficult to say, due to the decrease in the SWP sensitivity at the longward limit, the emission line profile of CIII] $\lambda 1909$ also appears to lack a red peak component (Figure 40). On the other hand, the emission line profile of Mg II $\lambda 2798$ (Figure 41) appears much more like the Balmer lines than C IV (but note that the red and blue wings of this line are heavily blended with Fe II multiplets). That the red peak appears to be present in the low excitation lines and absent in the higher excitation lines may be evidence for some

ionization stratification through the broad line region and perhaps for multiple physical/dynamical structures ($\text{Ly}\alpha$ is often associated with the high excitation zone; see Collin-Souffrin *et al.* 1988, and Netzer 1987). Similar evidence for ionization stratification in the BLR has been found in NGC 5548 (Peterson *et al.* 1990a,b; Wamsteker *et al.* 1990; Clavel *et al.* 1990b). Thus integrated line ratios, including Balmer decrements at best are giving us very smeared out or average information about the BLR, and at worst, meaningless or misleading information. This underscores the importance of at least isolating the broad emission line components in many broad lines, so that meaningful information may be derived from their ratios. The low S/N ratio and poor spectral resolution in the *IUE* scans do not allow us to comment on the blue shoulder in these data, and temper the claim for evidence of ionization stratification, especially since we cannot well estimate the narrow line contribution to the UV line profiles.

Figure 37. The mean He I $\lambda 5876$ profile of the 1987-88 observing seasons. Absorption due to Na I D $\lambda\lambda 5890, 5896$ are present near $+1000 \text{ km s}^{-1}$ (intrinsic to Akn 120) and near -8700 km s^{-1} (Galactic). Emission due to [Fe VII] $\lambda 5721$ is also present near -7900 km s^{-1} .

Figure 38. A mean of several IUE spectra of Ly α λ 1216. N V λ 1240 is present in the red wing near +6000 km s^{-1} .

Figure 39. A mean of several *IUE* spectra of C IV $\lambda 1549$. This profile bears little resemblance to any of the $H\beta$ profiles.

Figure 40. A mean of several *IUE* spectra of C III]λ1909. The red side of the profile is affected by the decrease in sensitivity at the long wavelength end of the SWP scan.

Figure 41. A mean of several *IUE* spectra of Mg II $\lambda 2798$. Although both wings are heavily blended with Fe II, the resemblance to the Balmer lines near the core is apparent.

E. The Origins of the Broad Line "Components"

and Profile Variability

1. Shocks?

Daltabuit, MacAlpine, and Cox (1978) proposed that shock ionization due to collisions between broad line clouds might contribute significantly to the AGN spectrum, specifically to the observed broad emission lines. The timescale between broad cloud line collisions is expected to be ~ 2 years or so for small BLRs (Mathews and Capriotti 1985) if the gas clouds are virialized. We have shown above that small broad line flux variations can mean significant broad line profile variations, and that the lifetime of a profile state is of the order of the timescale for cloud collisions. Differential changes in flux across the line profile might be the result of shocks due to cloud collisions. Shocks would not be correlated with the strength of the continuum, which also seems to be the case with profile variability. Figure 42 shows a simplified picture of two colliding broad line clouds. The much cooler regions ($\sim 10^4$ K) leading and trailing the shocked regions are photoionized "on the spot" through thermal Bremsstrahlung cooling of the neighboring hot ($\sim 10^8$ K) shocked regions. Line and bound-free continuum emission are also present in the cooling shocked regions, away from immediately behind the shock front where the gas has cooled some. Here we investigate the possibility that small scale flux variations due to shocks may account for the profile variability.

Figure 42. A schematic diagram of the collision of two broad line clouds, one from the left the other from the right. The symbols are as follows: *UC* - the undisturbed broad line cloud; *L* - the leading photoionized region, with a density that of the ambient cloud; *S* - the shocked region, which is cooling through thermal Bremsstrahlung emission (also line and free-bound continuum emission); *T* - the trailing photoionized region, which is highly compressed (note that the boundary between *S* and *T* is ill-defined); *N* - the high density (highly compressed) neutral region. The shock fronts are denoted by the heavy boundary marked *SF*. (Adapted from Daltabuit, MacAlpine, and Cox 1978).

We estimate the luminosity generated from the shock and the timescale of cooling and compare these with the observed luminosities and profile state duration (see Daltabuit, MacAlpine, and Cox 1978 for the detailed shock model and continuum and emission line calculations).

Recent photoionization models by Ferland and Persson (1989) and others suggest that broad line cloud column densities may be larger than 10^{24} cm^{-2} . For the canonical broad line region density of $10^{9.5} \text{ cm}^{-3}$, this implies cloud sizes of $\sim 10^{14.5} \text{ cm}$. From the Rankine-Hugoniot (adiabatic) shock equations, the following are derived:

$$N_s = 4N_u \quad (5)$$

$$v_s^2 = (0.25v_u)^2 = 0.2c_s^2 \quad (6),$$

where N_s , v_s , N_u ($= 10^{9.5} \text{ cm}^{-3}$, assumed), and v_u are the particle densities and speeds (with respect to the shock front) in the shocked and undisturbed regions, respectively, and c_s is the sound speed in the shocked region. From Figure 42 and equation 6 it is clear we may also relate the broad line cloud speed, v_c , with v_s :

$$v_c = 3v_s \quad (7).$$

From the definition of sound speed and equations 6 and 7, we find the temperature directly behind the shock front of

$$T_s \approx 10^{7.15} v_{c3}^2 \text{ (K)} \approx 10^8 \text{ K} \quad (8),$$

where v_{c3} is the cloud velocity in units of 10^3 km s^{-1} ; here we assume a cloud velocity of 3000 km s^{-1} .

The luminosity of the shocked gas due to thermal Bremsstrahlung cooling is roughly

$$L_{ff} \sim \epsilon_{ff} r^3 \approx 3 \times 10^{39} N_{10}^2 T_8^{0.5} r_{c14}^3 \approx 2 \times 10^{41} \text{ ergs s}^{-1} \quad (9)$$

for above parameters, while the ratio of the internal energy gained by the gas ($\sim NkT_g$) in the shocked region to the Bremsstrahlung emissivity is roughly the cooling time of the gas:

$$\tau_{cool} \sim 1.7 N_{10}^{-1} T_8^{0.5} \text{ days} \approx 1 \text{ day} \quad (10),$$

and the cloud interaction timescale is

$$\tau_{interaction} \sim 35 r_{c14} v_{c3}^{-1} \text{ days} \approx 1 \text{ month} \quad (11)$$

for the assumed parameters, where N_{10} is the density in the shocked zone in units of 10^{10} cm^{-3} , T_8 is the temperature in the shocked zone in units of 10^8 K , and r_{c14} is the cloud size in units of 10^{14} cm . The luminosity corresponds to about 10% of the total observed $H\beta$ luminosity, which, for this simple model, is within an order of magnitude to supply the energy for a change in the profile. However, the cooling time is far too short by 2 orders of magnitude, and more importantly the interaction timescale is too short by an order of magnitude, compared to the lifetime of the major profile states (sometimes as long as 1-2 years). Larger clouds could make up this discrepancy, although one must then explain why the cloud collisions occur in the same preferred places in radial velocity space over timescales of ~ 10 years or more (note that the cloud crossing time across the BLR in Akn 120 is $\sim R_{BLR}/v \approx 3\text{-}10$ years). Thus we conclude that shocks due to inter-cloud

collisions are a possibility in explaining some of the profile asymmetries and variability, but that problems still remain.

2. *A Discussion of Other Possibilities*

Not only is it likely that the roughly 4 "components" comprising the Balmer line profiles, as described above, are not Gaussian, but two or more of them may be due to the same physical/dynamical structure. For example, the red peak and blue shoulder may be the two peaks in an accretion disk, or due to emission from a bi-conical outflow (either of which also might include the very broad wings as well). If the changes in line and continuum fluxes as well as changes in the profile are ever temporally resolved, we would expect that the red peak and blue shoulder should vary in-phase, if they are the peaks of accretion disk emission. If, however, they are due to bi-conical outflow, the blue shoulder ought vary first, the red peak following, to a change in the continuum (unless they are oriented at a large angle to the line of sight, in which case they might be observed to change together). However, this behavior might be associated with any kind of outflow. It has been suggested that the central broad emission "filling in" the profiles of either an accretion disk or bi-conical outflow could be due to a "wind" (van Groningen 1984). A wind ought to be optically thin to the ionizing continuum and the Balmer emission should not be as variable as that emitted from optically thick gas (presumably the rest of the profile). To first order this would mean that the profile state should be correlated with the continuum strength, which apparently is not the case. A well resolved large continuum and emission line outburst with

high quality data might provide for a test of this model (Figure 23 might be such a case against this model, but the flux variation was small). Although the data do not allow us to distinguish one model over the other, they do reveal that the structure of the BLR is more complicated than any one of these.

Rather than representing multiple components, the individual bumps in the Balmer line profile might also be due to localized emissivity inhomogeneities (LEIs) within a single-component distribution of BLR clouds; i.e., a localized region in real space (corresponding to a localized region in velocity space) in which the local physical parameters, such as density or the ionizing flux, are different than and change relative to the surrounding regions. However, it is difficult to imagine how density inhomogeneities can persist at the same radial velocities for the long periods of time that the "bumps" have been observed, unless these regions of enhanced density are, for example, merely "density waves" or standing shocks (due to what?), rather than physical blobs. It is also a possibility that the exciting continuum as seen by the BLR clouds may be inhomogeneous; i.e., 1 or more of the components or bumps may be due to or enhanced by a beamed component to the continuum. And if the contribution of the beamed continuum becomes stronger relative to the unbeamed continuum, the line profile might change. There is evidence for beamed continua on the large scale in some radio loud AGN (and perhaps for some Seyfert galaxies on the kiloparsec scale), though it is yet unclear whether this is the case on the scale of the BLR. This hypothesis is not readily testable and, until some evidence for continuum beaming on the BLR scale arises,

somewhat *ad hoc*. At this point, LEIs within a single component do not appear to be a viable explanation for the profile asymmetries or variability.

The above arguments, the complex broad line profiles and their difference spectra, and the difference in profiles between the high and low ionization lines together argue strongly for a multicomponent BLR in Akn 120.

IV. Summary and Future Work

Following the calculations of Joly (1988) we have shown that additional Fe II multiplets (m25 and m36) can, along with Fe II m42, account for the "red shelf" under the red wing of $H\beta$. The resultant $H\beta$ profile is then much more similar to the rest of the Balmer lines, and the Balmer decrement of the "red peak" is not as flat as was once thought. Very little or no broad [O III] is required in the red shelf, and Si II $\lambda 5056$ is identified, which may be indicative of the importance of resonance fluorescence as an emission mechanism of Fe II in this Seyfert galaxy.

The 3 easily discernible "components" (the blue shoulder, central peak, and red peak) are persistent at the same radial velocities over long timescales (~ 10 years). The broad Balmer line components sometimes vary together, homologously, with the continuum over long timescales (~ 1 -2 years), during which the profile does not change significantly. There seems to be little or no correlation between the profile state and the strength of the continuum. However, sometimes the components change their strengths differentially, and the broad emission

line profile then varies significantly. The mechanism for change and the timescale on which this occurs are unknown, although the latter must be less than 5 months. Once the profile variation has occurred the profile can remain stable for another 1-2 years.

We have found several lines of evidence supporting the picture of multiple emitting regions within the broad line region of Akn 120. No fewer than 4 Gaussian-like components are present in the Balmer broad line profiles, although fewer (but more than 1) are possible if the component profiles deviate greatly from Gaussians. However, we have also shown that great care must be taken in the interpretation of difference profiles and of the results of profile fitting.

We have demonstrated the importance of temporal coverage to profile analyses to determine the structure of the BLR. High S/N and spectral resolution better than $9\text{\AA}$ also required. A monitoring campaign, such as the one recently carried out for NGC 5548 in the optical and ultraviolet (Clavel *et al.* 1990b; Peterson *et al.* 1990b), must be carried out for Akn 120, if we ever hope to understand the BLR structure in this AGN. In addition to significant changes in the continuum and broad line fluxes, the observations of significant variations in the broad emission line profiles during such a campaign are important. Hopefully, excitation inhomogeneities might also be temporally resolved, revealing the dominant motion (e.g., infall, outflow, rotation) of the BLR gas. We have also demonstrated the need to have such information for as many broad lines (at least $H\alpha$, $H\beta$, and the stronger UV lines) as is possible. The transfer functions for each of the emission lines could then be derived. At that point we should be able to at least rule out some

geometries. A profile variability study would then complement the flux variability analysis. It may also prove interesting to have transfer functions for two extreme profile states as they may result in different answers as to the structure of the BLR, especially if the BLR is truly multi-componented. Ultimately what is needed is a transfer function as a function of radial velocity.

Longer observing seasons (and better luck) would certainly improve our chances in catching Akn 120 in the act of varying in flux and profile. This is possible with the much more stable CCD spectrograph. Such a monitoring program, with temporal resolution of about 1 week, has been planned for Akn 120 and other Seyfert galaxies. Cooperation among observatories, such as that which took place for the NGC 5548 optical campaign (see Peterson *et al.* 1990b), would be essential due to the unreliability of good weather.

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CHAPTER IV
IMPLICATIONS OF AN OPTICALLY THIN VERY BROAD LINE
REGION IN ACTIVE GALACTIC NUCLEI

I. INTRODUCTION

The broad-emission line profiles of several Seyfert galaxies have been observed to vary. It has been hoped that the changes in the broad-emission line profiles would be indicative of the structure and dynamics of the broad-line region. It has been recently reported that difference spectra formed from high state and low state spectra show double peaked profiles, perhaps indicative of an accretion disk (Alloin, Boisson, and Pelat 1988; Stirpe, de Bruyn, and van Groningen 1988). This double peaked characteristic tends to be more pronounced in $H\alpha$ than in $H\beta$.

In order to determine whether or not double-peaked difference profiles are pervasive a search was made of the Ohio State University Image Dissector Scanner data archive for broad-emission line ($H\alpha$ and $H\beta$) profile variations in 4 Seyfert 1 galaxies (Mrk 79, Mrk 509, Mrk 590, NGC 4051) and 1 broad line radio galaxy (3C 120) in which there existed 12 or more observations each (excluding NGC 5548 and Akn 120), in which we looked specifically for the double peaked residuals. In addition we searched for profile variability in 6 other Seyfert 1 galaxies (Mrk 110, Mrk 618, Mrk 766, Mrk 871, NGC 3227, NGC 3516), with typically 5

observations each (Mrk = Markarian). Although continuum and broad emission line flux variations were observed in most cases, no significant broad emission line profile variability was found in any of the sample, with the exception of Mrk 590. Additionally, in the one case (Mrk 590) in which the broad emission line profile varied significantly between high and low states, there was no evidence for double peaked difference profiles in either $H\alpha$ or $H\beta$.

In the two Seyfert 1 galaxies for which many significant broad-emission line profile variations have been observed, namely Arakelian 120 (Foltz et al. 1981; Alloin, Boisson and Pelat 1988, Chapter III of this dissertation) and NGC 5548 (Peterson 1987; Peterson, Korista, and Cota 1987; Stirpe, de Bruyn, and van Groningen 1988; Peterson, et al. 1990a; Wamsteker et al. 1990), it has been suggested that the broad-emission lines are composed of multiple components which arise in spatially and kinematically distinct regions. However, because the emission-line components are generally heavily blended, very little information about the individual components has been reliably determined. If extreme broad-emission line profile variations are observed, the problem of isolating and investigating the individual components becomes easier. Such variations were observed for the Seyfert 1 galaxy Markarian 590.

In this paper we find that 2 distinct components contribute to the broad-emission Balmer line profiles in this Seyfert galaxy. We argue that the core of the line is emitted from the "classical" broad-line region (BLR), while the very broad line (VBL) is emitted by an optically thin, high covering factor gas well inside of the BLR, relative to the

central continuum source. Here we investigate the VBL component and find that such gas contributes to or can account for several heretofore unexplained phenomena in active galactic nuclei. In Section II we present the observations. In Section III we analyse the broad Balmer emission lines. We develop a model for the origin of the very broad line gas in Section IV and discuss the implications of its presence. Finally, we summarize our results in Section V.

II. OBSERVATIONS AND DATA REDUCTION

Most of the optical observations presented here were obtained with the Ohio State University Image-Dissector Scanner (Byard et al. 1981) on the 1.8-m Perkins telescope of the Ohio State University and Ohio Wesleyan University at the Lowell Observatory. These data were acquired with 7" circular entrance apertures and reduced as described by Peterson (1987). Of the 14 $H\beta$ and 4 $H\alpha$ IDS observations of Mrk 590, two of each are of primary interest in this paper and these are summarized in Table 9 and illustrated in Figure 43. From here on we refer to the data taken on Julian Date 2446377 as the "low state" and that taken on JD 2447412 and JD 2447413 ($H\alpha$ and $H\beta$ scans, respectively) as the "high state". Both sets of spectra have S/N of about 50, and spectral resolution of about 500.

All of the optical data have been put on a common flux scale by scaling them to the same flux in narrow $[O III]\lambda 5007$ which we assume to be constant over the timescales considered here.

Table 9
Dereddened Total Broad Line and Continuum Fluxes

Julian Date (2440000+)	$F_{\lambda}(5000\text{\AA})^1$	$F_{\lambda}(6120\text{\AA})^1$	$F(\text{H}\beta)^2$	$F(\text{H}\alpha)^2$
(1)	(2)	(3)	(4)	(5)
6377	1.73 ± 0.25	1.40 ± 0.14	3.82 ± 0.35	14.24 ± 1.15
7412	6.81 ± 0.22	5.00 ± 0.44	10.41 ± 0.94	33.44 ± 2.68

¹: non-stellar continuum fluxes in units of 10^{-15} ergs s^{-1} cm^{-2} $\text{\AA}^{-1}$

²: line fluxes in units of 10^{-13} ergs s^{-1} cm^{-2}

Figure 43. Two spectra of the Seyfert 1 galaxy Mrk 590, obtained on 1985 November 8 (JD 2446377) and on 1988 September 8, 9 (JD 2447412,13) (top frame), and their difference (bottom frame). Note the absence of the very broad emission line wings in the difference spectrum even though the line cores changed by large factors. The starlight contribution has been removed in each spectrum.

The most recent spectra of Mrk 590 were taken in 1989 September (2447777) and 1989 November (2447837) with the Ohio State University CCD spectrograph with a similar size aperture, and are our only truly photometric observations. They were reduced in the usual way with IRAF. We note in passing that these continuum and Balmer-line fluxes are slightly lower than those of the "high state" spectrum. We find the flux of [O III] λ 5007 to be $F(\lambda 5007) = (1.20 \pm .07) \times 10^{-13}$ ergs s $^{-1}$ cm $^{-2}$, in the rest frame of Mrk 590 ($z = 0.0263$). In the high state the H α scan has an 800Å overlap with the H β scan, allowing us to accurately scale the H α scan to the correctly scaled H β scan. The low state is a single scan containing both Balmer lines (all other observations of H α and H β were either simultaneous or within 3 days of each other).

There is no significant Galactic reddening for Mrk 590. Burstein and Heiles (1982) find a Galactic E_{B-V} of 0.01 magnitudes. However, we adopt an E_{B-V} of 0.045 mag, which corresponds to the Galactic hydrogen column derived from EXOSAT observations (Turner and Pounds 1989) and an assumed normal dust to gas ratio. We also expect very little intrinsic reddening as well, given that this galaxy is nearly face-on with an axial ratio of 0.97 (Adams 1977). De Zotti and Gaskell (1985) predict an intrinsic E_{B-V} of 0.15 for a Seyfert galaxy with the above axial ratio. This value plus the Galactic is probably a good upper limit.

Mrk 590 has a substantial starlight contribution to its continuum as observed through a 7" aperture. An estimate of the starlight contribution is made as described by Crenshaw and Peterson (1985). These authors subtract an appropriately scaled spectrum of M32 from the Seyfert (rest frame) spectrum. The flux scale factor for the M32

spectrum is chosen to minimize the strength of the stellar features in the residual Seyfert spectrum. We find the stellar contribution at 5000Å in a 7 arcsecond aperture to be $F_{\lambda}(5000\text{Å}) \approx 4.6 \times 10^{-15} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$. This subtraction has very little effect on the following analysis, which is based mainly on a difference spectrum formed by subtracting the low state spectrum from the high state spectrum, in which case the constant stellar contribution should completely subtract out.

III. ANALYSIS

A. Broad Balmer-Line Decontamination

In order to determine the broad $H\alpha/H\beta$ ratios and Balmer line fluxes discussed below with any degree of accuracy, the contributions of narrow emission line and broad Fe II must be taken into account. We list these contaminants and their estimated strengths in Table 10. In the case of $H\beta$ there are the following major contaminating lines: narrow $H\beta$, narrow $[\text{O III}]\lambda\lambda 4959, 5007$, and broad Fe II. The strengths of the two $[\text{O III}]\lambda$ lines are fairly easily measured (with $5007/4959 \approx 3$), and an estimate of narrow $H\beta$ is made by subtracting off a suitably scaled $[\text{O III}]\lambda 5007$ profile, as described by Peterson (1987). This is estimated to be $0.12F([\text{O III}]\lambda 5007)$. Although weak, even in the high state, the Fe II contribution is significant and the correction not as unambiguous. Besides the Fe II $\lambda\lambda 4924, 5018$ lines of multiplet 42, other multiplets (25 and 36) may contribute significantly to the total Fe II flux in the red wing and core of $H\beta$ (see Joly 1988).

Table 10

Dereddened Relative Line Fluxes of Major Contaminants

Line (1)	Relative Line Flux ([O III] $\lambda 5006.85 = 1.0$)
	(2)
[O III] $\lambda 4958.95$	0.338
H β $\lambda 4861.3$ (narrow)	0.12
Fe II (m25,36,42) (broad) in red wing of H β	0.25 (low state) 1.37 (high state)
[O I] $\lambda\lambda 6300.2, 6363.8$	0.26
[N II] $\lambda\lambda 6548.1, 6583.4$	0.71
H α $\lambda 6562.8$ (narrow)	0.45
[S II] $\lambda\lambda 6716.4, 6730.8$	0.23

Flux [O III] $\lambda 5006.85 = 1.2 \times 10^{-13}$ ergs s $^{-1}$ cm $^{-2}$

Starting with an estimate of the strengths of (m42) Fe II $\lambda 5169$ and of the Fe II complex near $4570\text{\AA}$ and relative line strengths from Joly (1988), we are able to estimate the total broad Fe II contribution to the measurement of broad H β (see Chapter III of this dissertation).

Narrow H α and [N II] $\lambda\lambda 6548, 6584$ are the major contaminants to the broad H α emission, while [S II] $\lambda\lambda 6717, 6732$, and [O I] $\lambda\lambda 6300, 6364$ are also significant contributors. The correction to the narrow H α is made in the same way as for the narrow H β ; we find a narrow-line H α /H β flux ratio of 3.75. The strengths of the narrow [O I], [N II] and [S II] lines are from Osterbrock (1977), corrected for reddening. All of these corrections are applied only to the measurements of the H α and H β fluxes. As with the starlight contribution to the spectrum, all of these are constant contaminants (with the exception of Fe II), and are expected to subtract out completely in the difference spectrum which forms the basis of our profile analysis below. The dereddened continuum fluxes at $5000\text{\AA}$ and $6120\text{\AA}$ and the corrected total fluxes of H β and H α are given in columns 2 and 3, 4 and 5, respectively, in Table 9.

B. Profile Variability

It is obvious from Figure 43 and Table 9 that, in the time span between the two observations of the high and low states (about 2.8 years), the continuum and Balmer-line flux increased dramatically. The continuum increased by a factor of 3.9 at $5000\text{\AA}$, while the total line flux in H β and H α increased by factors of 2.7 and 2.3, respectively.

Large changes in the broad Balmer-line profiles are also apparent in Figure 43. Similar extreme changes in the broad Balmer-line profiles

and strengths have been observed before (e.g. Mrk 1018: Cohen et al. 1986). It is especially apparent in the low state H α that the broad Balmer-line profile has two distinct components: a relatively narrow core (FWHM = 2600 km s⁻¹), which we identify as the "classical" broad-line region and designate NBL (narrow broad-line), and a strong very broad line (VBL), with a FWZI = 22000 km s⁻¹.

However, the lower panel of Figure 43, which shows the difference between the high and low states, demonstrates that only the NBL has increased in flux in response to the higher continuum. Note the contrast between its near absence in H β in the low state and its prominence in the high state. There is no indication of any VBL emission in either the H α or the H β residuals in Figure 43. Figure 44 shows the high and low state H α profiles with the continuum in each state subtracted. Note how well the very broad wings match, while the core varied by a large factor.

Taken at face value the emissivity of the VBL does not change when the ionizing flux striking it does change. Two other possibilities are (1) the VBL region (VBLR) is much further away from the variable continuum source than the "classical" broad-line region, or (2) we happened to observe the VBL in an intermediate state in either or both the high and low state spectra (e.g. a VBLR closer to the continuum source could have risen and fallen in response to a short duration continuum pulse before the narrow core could react). We reject the first alternative because of the extreme width of the VBL.

Figure 44. The low state and high state H α spectra with their continua subtracted. Notice how well the wings match, indicating that the very broad wings did not vary, even though the line core varied by a factor of about 6.

Twelve other $H\beta$ and 3 other $H\alpha$ observations between 1982 November and 1984 November, and an observation of both in 1989 September and of $H\beta$ in 1989 November show that while the NBL flux responds to changes in the continuum, as expected from the optically thick classical broad-line region, no corresponding changes in the VBL could be found. Although it is unfortunate that the high and low states were the only observations between 1985 November and 1988 September, our other observations do not support, and we find unlikely, the notion that the VBL was coincidentally in some intermediate state each time we observed it. We note that the Balmer lines were in a high state when G. Stirpe observed Mrk 590 on JD 2446807 and JD 2446808, about 1 year after our observation of the low state (Stirpe 1989). We suggest that future spectrophotometric AGN monitoring programs include Mrk 590 as a target.

C. Analysis of the Broad Balmer Line Components

As stated above we identify the NBL as the familiar broad-line region (BLR), and as such we do not investigate this component any further here, but restrict our discussion to the origin of the VBL. At this point we attempt to deconvolve the two broad-emission line components in the hope that line ratios (Balmer decrements and line ratios between the two components) and line fluxes will provide important information about the new emission line region (VBLR).

As noted above the two broad emission line components appear well defined in the low state $H\alpha$ profile where the contrast between the two is greatest. A simple eye estimate and a Gaussian fit to the VBL yield practically the same result, i.e., $F(H\alpha(VBL))/F(5007) \sim 8.6$. Another

method of isolating the VBL, which involved using the residual part of $H\alpha$ (the lower panel of Figure 43) as a template to remove the variable core, also gave similar results with a Gaussian-like profile shifted to $\geq +700 \text{ km s}^{-1}$ relative to the NLR. The FWHM of the Gaussian fit to the VBL is about 10000 km s^{-1} , almost a factor of 4 broader than that of the NBL. The above ratio corresponds to an $H\alpha$ (VBL) luminosity of approximately (to within a factor of a few) $1.3 \times 10^{42} \text{ ergs s}^{-1}$ ($H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$).

Since we have determined that the flux in the VBL is constant, the NBL contribution in both states was determined by simply subtracting the above result from the corrected total broad $H\alpha$ fluxes. A similar analysis on the low state $H\beta$ profile yields results with higher uncertainty, due to its lower flux. It appears and is therefore assumed that the NBL $H\beta$ component is very weak (though measurable) in this spectrum, and that most of the flux is due to the constant VBL (after correcting for the contaminants). The NBL contribution in the high state was determined then as in $H\alpha$ above. Table 11 lists the fluxes of the two broad emitting components (NBL and VBL) of $H\alpha$ and $H\beta$ in both states. Note that the NBL $H\alpha$ is nearly 6 times larger in the high state as in the low, while in $H\beta$ it is perhaps greater than an order of magnitude larger in response to the higher continuum level. By contrast, no change was detected in the VBL (Figures 43 and 44). The strength of the VBL emission, especially in $H\alpha$, and the very large differences in the line and continuum fluxes between the high and low states are thus other reasons we are confident that any possible change in the very broad wings was not just missed in the noise.

Table 11

Dereddened Broad-Emission Line Component Fluxes in H α and H β

Julian Date (2440000+)	NBL Fluxes ¹		VBL Fluxes ¹	
	H β	H α	H β	H α
(1)	(2)	(3)	(4)	(5)
6377	0.36	3.93	3.46	10.31
7412	6.95	23.13	"	"

¹: Component Fluxes in units of 10^{-13} ergs s⁻¹ cm⁻²

Table 12

Balmer Decrements $H\alpha/H\beta$ of the Emission-Line Components

Julian Date (2440000+)	Total	NBL	VBL	Residual	Narrow
(1)	(2)	(3)	(4)	(5)	(6)
6377	3.73	-10	3.0	2.9	3.75
7412	3.21	3.32	"	"	"

Table 12 lists the Balmer decrements ($H\alpha/H\beta$) for the total line and the individual components. Note the steeper decrement in the NBL component corresponds to the low state. This is observed in many Seyfert 1 galaxies and is an indication of a correlation of line optical depth with continuum luminosity in optically thick clouds (e.g., see Wamsteker *et al.* 1990). The observed decrement of the NBL component in the high state is typical of the BLR, while that of the varying part is approximately 2.9. The estimated decrement in the VBL component is $3.0(\pm 0.5)$, not very different from the high state NBL or the residual decrements. This is interesting in that it may suggest that certain conditions in the VBLR may not be vastly different from those in the classical BLR (such as extremely high densities: greater than 10^{12} cm^{-3} , as it has been suggested for the high velocity gas).

D. The VBLR: An Optically Thin, Large Covering Factor Component

We have thus far determined that the VBL emissivity is not correlated with changes in the continuum. In optically thick or radiation bounded media, such as the BLR gas, the emissivity does respond to changes in the ionizing continuum, since more gas is available to become ionized. This is the case for the NBL component which we have identified as the BLR gas. However, the emissivity of matter bounded or optically thin media does not change in response to changes in the ionizing continuum, since the gas is fully ionized (although small changes may be expected due to changes in temperature). As determined from the observations, then, we deduce that the VBL hydrogen gas is fully ionized and optically thin to the ionizing Lyman

continuum. Some evidence for non-varying broad Balmer line wings has also been found in NGC 5548 (Stirpe, de Bruyn, and van Groningen 1988) and Fairall 9 (Stirpe, van Groningen, and de Bruyn 1989). An optically thin contribution to the BLR has been suggested by earlier investigators for various reasons (Voit, Shull, and Begelman 1987; Morris and Ward 1989).

In both Balmer lines the VBL dominates the emission in the low state; even in the high state the VBL/NBL flux ratio is about 0.45 (see Table 11). This is significant for the following reason. The optically thick BLR gas can efficiently reprocess the ionizing continuum; the BLR covering factor ($\Omega/4\pi$) need only be on the order of ~ 0.1 (Baldwin and Netzer 1978) to account for its emission. However, optically thin gas is not an efficient reprocessor of the ionizing continuum, and yet the VBL produces nearly as much or more Balmer line emission than the optically thick BLR. This implies that the VBLR must have a much larger covering factor, close to unity (see also Ferland, Korista, and Peterson 1990).

Thus far we have found four important observational constraints for our model of the VBLR. It is optically thin, has a high covering factor, has a determined (within a factor of a few) $H\alpha$ luminosity, and an $H\alpha/H\beta$ ratio of approximately 3. In the following we describe our model and outline the results and predictions.

IV. The Origin of the VBL Emission and its Implications

Here we develop a model of the VBLR, as constrained by the observations. However, we assume that the VBLR is not unique to Mrk

590. Indeed, many other Seyfert galaxy spectra exhibit VBL emission, although whether it is emitted from optically thin gas has yet to be demonstrated for these other cases. Nevertheless, the results we present are meant to be generic to the AGN phenomenon, rather than specific to Mrk 590. We find that the VBL gas lies well inside the BLR, and that it emits Balmer lines and a wide variety of high excitation emission lines. Although our original intent was to model the observed very broad bases which we hypothesized to be optically thin, we soon discovered that the presence of the VBL gas may also explain the following AGN phenomena: (1) The continuum transmitted though this screen is significantly absorbed between a few Rydbergs and ~ 100 Rydbergs and could account for the soft ionizing continuum (the roll-over in the Big Blue Bump) incident upon the BLR in Seyfert 1 galaxies, as well as the observed variable soft X-ray absorption. The absorbed radiation is reprocessed and reemitted at lower energies as free-free radiation that could account for a significant fraction of the Big Blue Bump and the observed centimeter excess, as described in detail in Ferland, Korista, and Peterson (1990). (2) It can account for variable narrow absorption lines. (3) This gas forms a translucent electron scattering screen that reflects broad-line emission from the near side and attenuates it from the far side, affecting the broad-line emission profile.

A. The Model

Ionization and thermal equilibrium calculations were performed with the photoionization code CLOUDY most recently described by Ferland and

Rees (1988), Ferland and Persson (1989), and Rees, Netzer and Ferland (1989). Here we discuss our model input and assumptions, some of which are based upon the observational constraints given above.

1. The Model Continuum

Due to intervening absorption very little is known about the AGN ionizing continuum in the extreme ultraviolet, roughly between 13.6 eV and 0.1 keV. We use the mean AGN continuum deduced by Mathews and Ferland (1987), but with a submillimeter break at 10 microns, as described in Korista and Ferland (1989), Ferland and Persson (1989), and Rees, Netzer, and Ferland (1989). The break is chosen to prevent extreme free-free heating that would occur due to the submillimeter radiation. This cutoff is known to exist, just where is uncertain, but it probably lies somewhere between 10 and 80 microns (see Engargiola et al. 1988 for recent results). Tests show that within this range, the choice of the break has no significant qualitative effects on the following results, but affects only the details. This continuum was scaled to match the *HEAO-1* (2-20 keV) unabsorbed X-ray luminosity $\log(L_x(2-20 \text{ keV})) = 43.45$ for Mrk 590 (Tennant and Mushotzky 1983). This is consistent with the observed *EXOSAT* (1-10 keV) (Turner and Pounds 1989) and optical luminosities as well.

2. Model Geometry

From the profile analysis above it was shown that the VBL gas must have a large covering fraction. We assume a spherical geometry, full coverage, and some filling factor. The total hydrogen density is held constant through the model.

3. Other Assumptions

The chemical abundances in AGN near the central continuum source are not known. We assume approximately a solar abundance (see Rees, Netzer, and Ferland 1989).

We assume a microturbulent velocity field of 350 km s^{-1} , which has the effect of reducing the optical depths in the lines. This value is chosen to reflect the determined width (the "b" value) of the absorption lines observed superposed on the broad-emission lines in some Seyfert galaxies (NGC 4151: Bromage et al. 1985). While this width might be due to bulk motions, the net effect (increasing the bandwidth and lowering the optical depth) of either type of velocity field is nearly the same.

We also require all of the zones to be thermally stable; i.e., we require the derivative of the cooling function with respect to the temperature to be positive. Careful attention was paid to this.

Another observational constraint on the model derived from the above profile analysis is that the VBL gas must be optically thin to the Lyman continuum; hydrogen is fully ionized. This is an assumption included in the model. However, the model calculations are actually stopped when the optical depth at 0.5 keV reaches 23.3, which corresponds to a cold, neutral soft X-ray absorbing column of $10^{22.5} \text{ cm}^{-2}$ (Morrison and McCammon 1983), typical of many Seyfert galaxies.

Finally, our measurements of the $H\alpha/H\beta$ ratio and $H\alpha$ luminosity provide further constraints on the model.

B. Results: The VBL Gas

1. The Environment

With the given assumptions outlined above, the only remaining free parameters are the total hydrogen density N_H (cm^{-3}), which is assumed to be constant (with radius) throughout the model, the inner radius R_{in} (cm), and a constant (with radius) filling factor, ϵ . Some non-unity filling factor is expected, and the major effect of this is to give some geometrical thickness to what will otherwise be (with $\epsilon = 1$) an extremely thin sheet. These are varied to get results that fall within the observational constraints described above. We make no attempt here to explore the dynamics of VBL gas; although due to the VBLR's proximity to the massive central engine, both gravitational and radiative forces are probably large.

Figure 45 illustrates the region in $R_{in} - N_H$ space where the VBL gas is found as constrained by the observations, for a filling factor of 10^{-3} . These are densities that are typical or perhaps a bit higher than is typical of the BLR, with the inner radius well inside the BLR. We find for an AGN of this luminosity and a typical BLR density of $10^{9.5} \text{ cm}^{-3}$, the BLR should have a characteristic distance of ~ 50 light days from the central continuum source. This assumes a BLR ionization parameter of $10^{-0.5}$, which some continuum-line reverberation studies of other AGN suggest (e.g., see Peterson 1988).

Figure 45. The region in $R_{\text{in}}\text{-}N_{\text{H}}$ space that the Very Broad Line Region may lie, mainly constrained by the characteristic that the VBL gas is optically thin to the Lyman continuum (scaled to the continuum of Mrk 590). In this example a filling factor of 10^{-3} was assumed. Note that the border between regions of optical depth was chosen to be $\tau_{912} \approx 0.3$.

Figure 46. A plot of electron temperature as a function of radius in a typical model of the VBL region. The VBL gas is considerably warmer than that of the classical BLR.

We find a typical ionization parameter for the VBL gas at the inner edge (R_{in}) to be large:

$$U = \Phi(H)(N_H c)^{-1} \geq 3 \quad (12),$$

where $\Phi(H)$ is the flux of ionizing photons at the *inner face* of the cloud, N_H is the total hydrogen density (cm^{-3}), and c the speed of light. In this constant density model U will decrease through the VBLR as r^{-2} . Because of the high ionization parameter, the radiation to gas pressure ratio in the cloud is many and the cloud is dynamically unstable. Figure 46 shows a typical electron temperature distribution as a function of radius for the VBLR. This is a warm gas, i.e., significantly warmer than the classical BLR gas.

The success of the model is not dependent upon very specific physical conditions. Note from Figure 45 that, in this example, the VBL density can range within almost 2 orders of magnitude, while the inner radius may lie anywhere between ~ 2 to ~ 11 light-days. Simultaneous UV VBL emission line strength measurements might further constrain the models. Generally speaking, the valid region in Figure 45 where the VBLR may lie in R_{in} - N_H space is bounded on the top and left by too large Lyman continuum optical depths. For inner radii smaller than ~ 2 light days the model predicts too little Balmer emission relative to our measurement of the Balmer VBL emission in Mrk 590. It is, of course, possible that the VBLR in some Seyfert galaxies lies in this latter region in Figure 45, and thus may have significant higher excitataion VBL emission and weak Balmer VBL emission. This may be the case in NGC

5548, for instance, in which the very broad bases are observed in the high excitation lines, but are weaker in the Balmer lines (Peterson *et al.* 1990a; Wamsteker *et al.* 1990). Densities larger than 10^{10} cm^{-3} start to result in geometrically ever thinner VBL regions, with $\Delta R/R \sim 0.33$ for 10^{10} cm^{-3} and down to ~ 0.09 for a density of 10^{11} cm^{-3} (for a filling factor of 10^{-3}), where ΔR is the thickness of the VBLR. At much larger densities the $H\alpha/H\beta$ ratio tends to become too flat. We find that filling factors near 10^{-3} ($10^{-2} - 10^{-4}$) give the best results. The range in filling factors is basically bounded by the observational constraint that the gas is optically thin to the Lyman continuum. These results are in agreement with the estimates made in Ferland, Korista, and Peterson (1990) based upon VBL emission measure arguments.

2. Emission Line Results

Table 13 lists some of the prominent lines emitted from the VBLR and their typical relative strengths. Very broad bases have been reported for $\text{Ly}\alpha$, N V, C IV, He II and the Balmer lines in other Seyfert galaxies (see, for example, Alloin, Boisson and Pelat 1988; Peterson *et al.* 1990a; Wamsteker *et al.* 1990). The only *IUE* spectrum taken of Mrk 590 did not coincide with any optical observations, and it was probably in a very low state as evidenced by an anomalously low $\text{CIV}\lambda 1549/H\beta$ ("low state") ratio of ~ 5.6 . Typical values for simultaneous optical/UV observations in Seyfert galaxies are greater than or equal to 10, and this would be the case here if there is as much intrinsic reddening as De Zotti and Gaskell (1985) estimate. However, it is also possible that the *IUE* observation was taken during a fainter state than even the low

state optical observation. The ratio may also change significantly at low continuum levels. Because of the low signal-to-noise of the *IUE* spectrum and because contemporaneous optical data are unavailable, even a crude profile analysis is not possible for the UV lines; this is unfortunate since such an analysis would have placed further important observational constraints on the model, e.g. N_H and R_{in} in Figure 45. Table 13 indicates that the intensity of the O VI $\lambda 1035$ line is predicted to be large. However, the strength of this line is rather dependent on the details of, among other things, the shape of the incident continuum, which is not known. It is also true that O VI $\lambda 1035$ is not observable in the Seyfert galaxies; redshifts greater than about 0.25 are needed for *IUE* to reliably observe it. Thus we have no way of knowing just how strong it is in Seyfert galaxies. We expect that the VBL gas would be generally somewhat more highly ionized in the higher luminosity objects (since X-ray columns are generally not measured), and thus their VBL emission may be very different than that in Seyfert galaxies.

While hydrogen is fully ionized within the VBLR (most of the helium is also fully stripped) and is expected to vary only weakly with the ionizing continuum, this is not true of the collisionally excited lines (or of the diffuse continuum emitted by the gas) which are much more temperature sensitive. Small changes in the emission line emissivity may also be brought about through changes in the mass flux through the VBLR. This can happen on a crossing timescale

$$\tau_{cr} \approx \Delta R/v \sim 3 \times 10^{16} \text{ cm} / 10^9 \text{ cm s}^{-1} \approx 1 \text{ year} \quad (13).$$

Table 13

Very Broad Line Emission Strengths for a Typical Model

Line		VBL Relative Strength
(1)		(2)
H α	$\lambda 6563$	2.81
H β	$\lambda 4861$	1.00
He II	$\lambda 4686$	1.02
He II	$\lambda 1640$	9.60
C IV	$\lambda 1549$	10.37
N V	$\lambda 1240$	2.75
Ly α	$\lambda 1216$	39.13
O VI	$\lambda 1035$	67.50

C. AGN Phenomena Explained by Presence of VBL Gas

After more than a quarter century of study there remain many important observed phenomena in AGN that are not understood. We have already suggested the origin of the very broad line emission; however, in addition to emitting line radiation, the presence of this VBL gas may account for five other previously unexplained phenomena.

1. The Incident Continuum to the BLR

a. The Soft X-Ray Absorber

Heavy soft X-ray absorption is common for low X-ray luminosity objects (i.e. Seyfert galaxies), with absorbing optical depths well above typical Galactic values (Reichert *et al.* 1985). It is not dust (see, for example, Mushotzky, Holt, and Serlemitsos 1978; Savage and Mathis 1979). It had been previously assumed that the absorption is due to a "cold" absorber, namely the BLR clouds (e.g. Mushotzky and Ferland 1984; Reichert, Mushotzky, and Holt 1986; and references therein). Figure 47 illustrates the predicted emergent spectrum from the VBL gas. Note the strong soft X-ray absorption. In our model the high covering factor VBL gas is the soft X-ray absorber observed in Seyfert spectra. In this model a varying continuum luminosity changes the state of ionization in the gas which changes the absorption cross section, that in turn accounts for the observed variability in the soft X-ray absorption. In Figure 48 we demonstrate how for this model the inferred cold, neutral soft X-ray columns change as a function of the continuum luminosity (the total column and inner radius are held constant). Even small changes in the continuum luminosity significantly affect the soft

X-ray optical depth. This is similar to the "warm" absorber model discussed by Halpern (1984), and Pan, Stewart, and Pounds (1990) to explain the soft X-ray absorption variability in the QSO MR 2251-178 (see also Nandra, Pounds, and Stewart 1989; Pounds *et al.* 1990).

Figure 47. A portion of the continuum incident upon the VBLR (heavy dots) and the continuum transmitted through the VBLR (solid line). Note the rollover in the ultraviolet continuum, as has been inferred for Seyfert galaxies, and the soft X-ray absorption. The "soft" transmitted continuum is then incident upon the classical BLR.

Figure 48. The logarithm of the total cold soft X-ray column (cm^{-2}) is plotted as a function of the logarithm of the continuum luminosity in units of the chosen luminosity of Mrk 590. The total hydrogen density, the inner radius and the total column are held constant, while the luminosity varies. See text for further explanation.

Furthermore, in this model the variable K-edges of carbon and oxygen may account for the observed variable soft X-ray excesses, as in Ferland and Rees (1987).

Soft X-ray absorption is generally not observed in objects having unabsorbed X-ray luminosities $\log (L_x (2-10 \text{ keV})) > 43.5 \text{ ergs s}^{-1}$ (which is the case for MR 2251-178), while it is common in objects having lower luminosities (Reichert *et al.* 1985; Reichert, Mushotzky, and Holt 1986; Turner and Pounds 1989). However, there are still other exceptions (Turner and Pounds 1989), and the luminosity boundary may not be so distinct. We expect and Figure 48 demonstrates that at high luminosities the VBL gas becomes too highly ionized to effectively absorb the soft X-rays. However, it is interesting and significant to note that the QSO MR 2251-178 is exceptional not only because it shows strong soft X-ray absorption, but that its H α profile exhibits very strong VBL emission, with a FWZI of $\sim 23000 \text{ km s}^{-1}$ (Canizares, McClintock, and Ricker 1978). Such VBL Balmer emission in this QSO may be indicative that the VBLR in this AGN is "neutral" enough to absorb soft X-rays, as many Seyfert galaxies do. We note that at large (QSO) luminosities Figure 48 (and similarly Figure 49) becomes highly schematic; the situation is probably more complicated in real objects such as MR 2251-178. However, it is not unreasonable to extrapolate that the same mechanism responsible for the soft X-ray absorption variability in lower luminosity AGN (gas ionization state a function of the continuum luminosity) is also the reason for the lack of absorption in higher luminosity AGN.

Typical absorbing columns, assuming a cold neutral absorber, are $10^{21} - 10^{23} \text{ cm}^{-2}$. However, this model predicts that because the VBL gas is highly ionized, the total column densities inferred from the X-ray measurements may be too low by factors of many (3-10, or more). Work here is still in progress.

b. The Soft Ionizing Continuum

Because the VBLR is predicted to lie well within the BLR and to cover a large portion of the ionizing continuum source, Figure 47 represents not only the transmitted continuum through the VBLR, but, schematically, the incident continuum upon the BLR. This is very similar to the "soft" ionizing continuum, or the roll-over of the Big Blue Bump (BBB), deduced by Binette *et al.* (1989), and Clavel and Santos-Lleo (1989) for the Seyfert 1 galaxy Fairall 9. They find that very little ionizing radiation should be incident upon the BLR clouds beyond $\geq 50 \text{ eV}$, as is shown in Figure 47. Clavel and Santos-Lleo predict the BBB roll-over to be common among Seyfert galaxies, which they contrast to the high luminosity QSOs that do not exhibit such a roll-over (at least not as soft). This model can account for the reason why the soft rollover in the BBB is not observed in high luminosity AGN. As we have demonstrated for the case of lower luminosity objects, i.e., Seyfert galaxies, the VBL gas heavily absorbs the continuum beyond a couple of Rydbergs. However, it is conceivable and calculations show that at much higher luminosities the VBL gas is more highly ionized (QSOs generally have small soft X-ray columns), and therefore becomes less efficient at absorbing the incident radiation beyond ~ 1 Rydberg.

Thus, in this scenario the BLR is irradiated with a harder continuum in higher luminosity objects, as has been deduced and observed (see also Ferland, Korista, and Peterson 1990).

c. The Origin of the Big Blue Bump in AGN Spectra

The origin of the Big Blue Bump (BBB) has been disputed since the discovery of its existence. Understanding the nature of the BBB is important, since much of it is the source of a significant fraction of the ionizing continuum. The fashionable theory at present is that the big bump is due to 30000 K modified blackbody emission from an accretion disk surrounding a supermassive black hole (Malkan 1983; Czerny and Elvis 1987; Madau 1988; Laor and Netzer 1989; Sun and Malkan 1989). However, it has been suggested by Ferland and Rees (1988) that it is due to diffuse reemission of high-density filaments surrounding the central continuum source. As discussed above and Figure 47 shows, the highly ionized gas of the VBLR, while transparent to relatively soft ionizing radiation (i.e., $h\nu < 50$ eV), strongly absorbs the harder ionizing radiation ($50 \text{ eV} < h\nu < 0.5\text{-}1$ keV) (however, we note here that the incident continuum in Figure 47 is not relevant here, since it already includes a big bump). This absorbed radiation, possibly from an incident underlying power law rather than from the input spectrum in Figure 47, is reprocessed and reemitted as mainly free-free and some free-bound radiation (similar in spirit to Ferland and Rees 1988). As described in detail by Ferland, Korista, and Peterson (1990), we find that the BBB has its origin in this diffuse reemission from the VBLR. The low energy tail of this diffuse emission extends to radio

frequencies and produces the centimeter excess observed by Antonucci and Barvainis (1988) in a sample of high luminosity Seyfert 1 galaxies and radio quiet QSOs. They too suggested diffuse optically thin free-free emission as the source of the centimeter excess, and found that the extrapolation of this radio continuum to ultraviolet frequencies was in good agreement with the BBB (Antonucci and Barvainis 1988; Barvainis 1990a,b). This diffuse emission should vary with changes in the underlying intrinsic ionizing AGN continuum.

In regards to the above 3 interactions between the continuum and the VBLR gas, further modeling remains using a more sophisticated "guess" to the intrinsic AGN continuum that is incident to the VBLR gas (as noted above the chosen continuum is not applicable for these purposes). The shape of the resulting blue bump emission will be important. It can be compared to the observable portion of the observed blue bump in AGN, and the model transmitted continuum may be utilized as a variable incident continuum for BLR emission line models, the resulting line ratios compared to observations (as in Clavel and Santos-Lleo 1990). Constraints might then be placed on possible models of the spectral energy distribution of the intrinsic AGN ionizing continuum.

2. Narrow Absorption Lines

Narrow absorption has been observed in a number of species of different ionization levels in four Seyfert 1 galaxies (mainly within the UV broad-lines and observed by *IUE*). They generally lie a few to several hundred km s^{-1} blueward of the systemic velocity and the emission-line center. The absorbing gas covers the continuum source and

possibly part of the BLR, and is generally believed to be in the vicinity of the BLR if not the BLR gas itself (see, for example, Bromage et al. 1985; Wamsteker and Barr 1985; Voit, Shull, and Begelman 1987). This model predicts that the VBL gas is also responsible for the narrow absorption lines. It also predicts absorption-line variability, with the absorption-line equivalent width a function of the continuum strength. For example, in a typical model the absorption equivalent width of C IV $\lambda 1549$ varies inversely with the continuum, as observed in NGC 3516 for C IV $\lambda 1549$ by Voit, Shull, and Begelman (1987), and in NGC 3783 for Si III $\lambda 1303$ by Wamsteker and Barr (1985), and in NGC 4151 for the low excitation lines (Bromage et al. 1985). The optical depths of some lines seen in absorption are shown as a function of continuum luminosity for a typical model in Figure 49.

Figure 49. Same as Figure 48 except that the ordinate is the logarithm of the optical depth at a particular wavelength. Except for O VI $\lambda 1035$, these are optical depths of lines that have been observed in absorption, superposed upon the broad-emission, in Seyfert spectra. See text for further explanation.

The optical depths of the absorption-lines vary as the continuum changes (with all else equal), which results in varying absorption-line equivalent widths. Note that a direct proportion between the equivalent width and luminosity may be true in some cases: C IV $\lambda 1549$ in NGC 4151 (Bromage et al. 1985), C IV $\lambda 1549$ and Si IV $\lambda 1400$ in NGC 3783 (Wamsteker and Barr 1985). The non-monotonic behavior of the N V $\lambda 1240$ and O VI $\lambda 1035$ optical depths in Figure 49 are examples of this (the optical depths at the other wavelengths would eventually roll over at lower luminosities in this example). The ionization state of the gas changes with the continuum, with the particular ionization zone moving through the VBLR as the luminosity changes. Our models show that depending on the physical conditions of the VBLR gas (e.g., the nominal continuum luminosity, N_H and R_{in} , i.e., the ionization parameter) specific to a particular Seyfert galaxy, an increase in luminosity can either increase or decrease the size of an ionization zone (the ion's column) lying within the VBLR, which is related to the optical depth. This would explain the varied behavior and strengths of the absorption-lines of different ionization species in different Seyfert galaxy spectra. Figure 49 also suggests why, in this scenario, the narrow absorption-lines are not observed in high luminosity objects; we predict that in these objects the absorbing gas (VBLR) is too highly ionized, as indicated by the lack of soft X-ray absorption. One QSO that has variable narrow Ly α absorption (Ulrich 1988), MR 2251-178, also has variable soft X-ray absorption, as well as strong Balmer VBL emission.

It has been previously suggested that (1) the soft X-ray absorption and the narrow UV resonance-line absorption are due to the same gas

(Ferland and Mushotzky 1982; Perola *et al.* 1986; Reichert, Mushotzky, and Holt 1986; Ulrich 1988), although many of the earlier investigators believed it to be the BLR gas. Wamsteker and Barr (1985) and Voit, Shull, and Begelman (1987) were not of this opinion and suggested the narrow absorption line gas is (2) optically thin, (3) outflowing gas. However, we believe at least the first two hypotheses to be true and the third is plausible as manifestations of the VBL gas. The soft X-ray absorption and the narrow-absorption variabilities ought to be correlated together with the continuum; both types of absorption should generally occur together. The VBL gas covers and absorbs the continuum source. It may also obscure a portion of the far side of the BLR (depending on the BLR geometry). Our model, therefore, predicts that the narrow-absorption-line phenomenon to be a general one in Seyfert galaxies (especially in those which show significant soft X-ray columns), although not necessarily present at all times. The existence of other (weak) absorption-line Seyfert galaxies is possible, and given the low spectral resolution and signal-to-noise of *IUE*, it is not surprising that they should remain undetected. Why the absorption lines are generally observed to be blueshifted and how this fits in with this model still remain to be explained. *HST* should help to resolve some of these unknowns.

3. An Electron Scattering Screen

Another important characteristic of the VBL gas is that it has a significant optical depth to electron scattering, typically $\tau \sim 0.1$. Shields and McKee (1981), Kallman and Krolik (1986), and van Groningen

and van Weeren (1989) have investigated hot ($\sim 10^7$ K) electron scattering sources of similar optical depths in order to explain either very broad wings or line asymmetries and shifts; the same hot medium is assumed to confine the broad-line clouds (but see Mathews and Ferland 1987). Electron scattering has also been investigated in the context of a warm medium to explain the broad-line emission seen in polarized light in NGC 1068 and other Seyfert 2 galaxies (Antonucci and Miller 1985; Krolik and Begelman 1986), or to explain the "high-frequency excess" observed in luminous Seyfert 1 nuclei and radio quiet QSOs by Antonucci and Barvainis (1988). However, in our model the VBLR, which is a warm gas surrounding the central continuum source and lying inside the BLR, forms a translucent electron scattering screen. This screen acts to reflect the broad-line emission from the near side and attenuate some of it from the far side. It also slightly broadens the emission profiles from the VBLR emission and the reflected portion of the BLR emission. The width of an electron scattering profile from the VBLR is approximately 2000 km s^{-1} FWHM (Shields and McKee 1981). This electron scattering screen is expected to be present in QSOs and Seyfert galaxies both, since the VBL electron scattering optical depth does not diminish with increasing state of ionization, as do the narrow absorption and soft X-ray optical depths. This may then be an alternative, or perhaps a complementary, explanation to the Kallman and Krolik model for the Ly α asymmetry conundrum, and may explain other broad-line asymmetries and shifts as well (e.g. Gaskell 1982). Ly α emitted from optically thick clouds (i.e. the BLR) only escapes from the side of the cloud facing the continuum source; therefore, its emission line profile ought to

appear asymmetric if the clouds are dominated by radial flow. However, the Lyman-alpha profiles are observed to be symmetric. The electron scattering screen is capable of reflecting back to the observer those Lyman-alpha photons emitted on the far side of the optically thick BLR cloud that otherwise would not be observed. An analysis of just how this electron scattering screen affects the broad-line profiles (given certain assumptions, such as the BLR geometry and dynamics) needs to be done, but it is beyond the scope of the present work.

V. Summary

In order to explain the very broad wings/bases observed in many broad-emission line object spectra, we have hypothesized the existence of a new component to the broad-line regions in AGN: an optically thin, high covering factor gas lying very near to the central continuum source. The new component is important, since it can explain many phenomena of AGN. The very broad-line gas, while transparent to photons in the Lyman continuum, absorbs photons in the energy range $50 \text{ eV} \leq h\nu \leq 500 \text{ eV}$ (approximately). The VBL gas then accounts for the inferred soft ionizing continuum incident on the BLR gas and the observed soft X-ray absorption. This "lost" energy is reprocessed and redistributed to longer wavelengths in the form of diffuse free-free emission which can account for the Big Blue Bump in the spectra of active galaxies. The low energy tail of this diffuse emission then accounts for the "centimeter excess" observed in luminous Seyfert 1 galaxies and radio quiet QSOs. Because the absorbing gas is highly ionized the presently inferred soft X-ray columns may be too low by factors of many (3-10).

In addition, the observed narrow line absorption takes place in the VBLR gas, and this same gas is an electron scattering screen which can affect broad-line region emission line profiles. The narrow absorption lines and the soft X-ray absorption together ought to vary with the ionizing continuum, while the VBL Balmer emission should not; these are observational tests of our model. More can be done both observationally and theoretically to better constrain this model.

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CHAPTER V

THE ORIGIN OF CORONAL LINES IN SEYFERT GALAXIES

I. INTRODUCTION

The broad permitted emission lines observed in active galactic nuclei (AGN) originate in gas having densities greater than 10^9 cm^{-3} , from a region less than a parsec from the central continuum source. The narrow lines are emitted in regions of densities 10^3 - 10^6 cm^{-3} lying 10 to 10^3 parsecs out. Photoionization by the central continuum source is probably the dominant ionization mechanism in both regions. However, the very high excitation forbidden lines of [Fe VII] λ 6087, [Fe X] λ 6375, [Fe XI] λ 7892 and [Fe XIV] λ 5303 (the so called iron "coronal" lines) do not seem to fit into either of the above niches. These lines may have widths intermediate between the lower excitation narrow lines and the broad lines, and are usually blueshifted relative to the lower-excitation narrow lines (DeRobertis and Osterbrock 1984, 1986; Grandi 1978; Osterbrock 1981; Osterbrock and Pogge 1985; Penston *et al.* 1984). The critical densities of the coronal lines ($\sim 10^7 \text{ cm}^{-3}$ for [Fe VII] to $\sim 10^{10} \text{ cm}^{-3}$ for [Fe X]) are also intermediate (DeRobertis and Osterbrock 1986); [Fe X] λ 6375 could originate in regions as dense as $6 \times 10^{11} \text{ cm}^{-3}$ (Penston *et al.* 1984), although there is no observational lower limit to the density. The above observations, plus the possible relationship

between a narrow forbidden line's FWHM and its ionization potential or critical density (DeRobertis and Osterbrock 1984,1986; Osterbrock 1981; Filippenko and Halpern 1984), suggested to earlier investigators that the "coronal" line region (CLR) lies within a transition zone between the broad-line region (BLR) and the narrow-line region (NLR), a zone of intermediate densities and velocities. All previous "scenarios" for the formation of the coronal lines (there have been few self-consistent calculations) have assumed this.

Previous investigations have postulated that the CLR is either a hot (10^6 K), collisionally ionized gas (Oke and Sargent 1968; Nussbaumer and Osterbrock 1970), or a cooler gas (10^4 K) photoionized by the central continuum source (Osterbrock 1969; Nussbaumer and Osterbrock 1970; Grandi 1978). Photoionization in combination with shocks has also been proposed (Viegas-Aldrovandi and Contini 1989). Here we investigate a very simple origin of the coronal lines, in the spirit of the second hypothesis. The AGN phenomenon is known to occur within a galactic environment (see Begelman 1985; Chang, Schiano and Wolfe 1987). We show that a typical galactic interstellar medium ($N_e \sim 1 \text{ cm}^{-3}$) photoionized by a "bare" Seyfert nucleus is all that is required to produce the coronal lines.

In Section II, we discuss coronal line formation. The results of our model along with comparisons with observations are presented in Section III. Finally, a summary is provided in Section IV.

II. LINE FORMATION

A. Photoionization Code and Atomic Data

Ionization and thermal equilibrium calculations were performed with the photoionization code "Cloudy" most recently described by Ferland and Rees (1988) and Ferland and Persson (1989). Here we discuss some details relevant to coronal line formation.

Iron photoionization cross sections, recombination coefficients, and collisional ionization rate coefficients are taken from Reilman and Manson (1979), Woods, Shull and Sarazin (1981), and Arnaud and Rothenflug (1985), respectively. The collision strengths are from Mason (1975) (Fe X, Fe XI, and Fe XIV) and Nussbaumer and Storey (1982) (Fe VII); the transition probabilities for the iron coronal lines are from Smith and Wiese (1973), Mendoza and Zeippen (1983) and Fuhr *et al.* (1981). Charge transfer rate coefficients for reactions between iron and hydrogen come from Neufeld (1984), and K-shell fluorescent yields from Krolik and Kallman (1987). We know of no calculation of rate coefficients for iron dielectronic recombination through low-lying autoionizing states. This makes the ionization balance uncertain by roughly a factor of 2.

B. Radiative Pumping and Collisional Excitation

Many iron lines can be both collisionally excited and radiatively pumped by electron dipole transitions in the extreme ultraviolet (near 300Å). For temperatures typical of the solar corona ($T \sim 10^6$ K) collisional excitation of these lines occurs mainly via excitation to higher lying levels, followed by radiative decay to the upper level of

the observed transition, and effective collision strengths which incorporate these decays are often defined (see, for example, Mason 1975). For the present application temperatures are too low for this to occur, and tests show that collisional excitation directly to the upper level of the observed transition is the major contributor to the collisional rate. Energy level diagrams for the ions we model are shown in Figure 50; the ultraviolet pumping mechanisms we include are also shown along with the coronal line transitions themselves. For [Fe X] $\lambda 6375$ ($2P^o_{3/2} - 2P^o_{1/2}$) we include collisional excitation to $2P^o_{1/2}$ from the ground state and electric dipole continuum pumping to $2S_{1/2}$ from the ground state ($\lambda 345.75\text{\AA}$) and subsequent decay to $2P^o_{1/2}$ ($\lambda 365.57\text{\AA}$), populating the upper level of the 6375 $\text{\AA}$ line. For [Fe XIV] $\lambda 5303$ ($2P^o_{1/2} - 2P^o_{3/2}$) we include collisional excitation to $2P^o_{3/2}$ from the ground state and electric dipole continuum pumping to $2D_{3/2}$ from the ground state ($\lambda 334.15\text{\AA}$) and subsequent decay to $2P^o_{3/2}$ ($\lambda 356.60\text{\AA}$). Collisional excitation to $3P_1$, $3P_0$ and electric dipole continuum pumping to $3P^o_1$ ($\lambda 341.115\text{\AA}$) and $3P^o_2$ ($\lambda 352.680\text{\AA}$) from the ground state of Fe XI are included for the $\lambda 7892\text{\AA}$ line ($3P_2 - 3P_1$). Here we neglect collisional deexcitation of $3P^o$, a good assumption under the physical conditions considered here. The [Fe VII] $\lambda 6087$ line is a $3F_3 - 1D_2$ transition. Continuum pumping does not contribute to this line due to forbidden spin changes that must occur, thus no fluorescence. Collisional excitation to the upper level is considered (Nussbaumer and Osterbrock 1970; Nussbaumer and Storey 1982; Sugar and Corliss 1985).

Figure 50. Illustrated here in these partial Grotrian diagrams are the continuum pumping transitions and the four iron coronal line emission transitions considered in this model. The [Fe VII] $\lambda 6087$ transition is (lower - upper) $3F_3 - 1D_2$, that of [Fe X] $\lambda 6375$ is $2P^{\circ}_{3/2} - 2P^{\circ}_{1/2}$, that of [Fe XI] $\lambda 7892$ is $3P_2 - 3P_1$, and that of [Fe XIV] $\lambda 5303$ is $2P^{\circ}_{1/2} - 2P^{\circ}_{3/2}$.

The ultraviolet pump transitions become optically thick (with optical depths of many); we assume the formalism of Ferland and Rees (1988) and a *microturbulent* velocity field of 350 km s^{-1} , which has the effect of increasing the bandwidth and reducing the optical depth within the pump transitions (τ becomes 0.719 from 62.6 for the [Fe X] pump transition, 0.522 from 37.9 for [Fe XI], and 0.260 from 11.0 for [Fe XIV] for an interstellar medium [ISM] density of 1.0 cm^{-3}). The value was chosen to reflect the observed line width of the [Fe X] $\lambda 6375$ line in NGC 4151 (Penston *et al.* 1984). Much of the observed width is actually due to bulk motions (*macroturbulence*), but the effect of either velocity field on the pumping rate is nearly the same. These pumping transitions are important, as they often produced more than 50% of the line intensity. It is important to remember that the actual continuum shape near $\sim 300\text{\AA}$ (the region most efficient in pumping the iron lines) is largely unexplored; this is an unavoidable uncertainty in addition to the uncertainty in the atomic data (many of the transition probabilities for the iron ions are uncertain by a factor of two, according to Fuhr *et al.* (1981); the model does not include iron dielectronic recombination through low-lying autoionizing states, since these recombination coefficients have not been computed). As a result we anticipate at least a factor of two uncertainty in the predicted line fluxes, and shall consider any better agreement between observation and prediction to be a success.

C. The Model Continuum

We use the mean AGN continuum deduced by Mathews and Ferland (1987), but with a break in the infrared continuum at $10\mu\text{m}$; the wavelength of this submillimeter break has no effect on the following calculations. The continuum intensity is scaled to NGC 4151's flux at $912\text{\AA}$ (we assume $\nu L_\nu(912\text{\AA}) = 10^{43} \text{ erg s}^{-1}$ from Ferland and Mushotzky (1982) for an H_0 of $55 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and a distance to NGC 4151 of 20 Mpc) in order that we can make semi-quantitative comparisons of line luminosities, line ratios and other physical phenomena for this object. However, we choose a mean AGN continuum so that our model can be as general as possible to explain a common phenomenon in Seyfert galaxies and do not intend to model the CLR in any one particular AGN. In Figure 51 we show a portion of the incident continuum (*solid line*) (the resulting transmitted spectrum [*dots*] will be discussed later).

D. Model Geometry

Although the distribution of the ISM is not as well known near the centers of spiral galaxies (or Seyferts) as in the outer regions, we assume a flattened geometry like that of the latter region. The disk of our model has an inner radius of 10 pc (the conventional inner radius of the NLR) and an outer radius of 2 kpc, and a semi-thickness of 100 pc (about one gas and dust scale-height in the spiral arm region of the Galaxy [Mihalas and Binney 1981]).

Figure 51. Part of the incident continuum (solid line) and the resultant transmitted spectrum (dots) for a hydrogen density of 0.5 cm^{-3} , plotted in $\log(\nu F_\nu)$ vs. $\log \nu$ (Rydberg) units. Note the Lyman limit absorption, the He II edge, and the various K-shell absorptions.

Figure 52. Same as Figure 51 except for a hydrogen density of 1.0 cm^{-3} . The line of dots near ten Rydbergs are off scale and lie much lower. Note the prominent Lyman limit, He I and He II edges. Note also some re-emission in the blue/near-UV due to balmer continuum emission.

The choice of outer radius was set by the requirement that the CLR extend to at least the observed radii of some of the Seyfert nucleus-excited *extended* narrow-line regions (ENLR) observed (Heckman and Balick 1983; Schulz 1988; Unger *et al.* 1987, 1988; and others). We also investigated a spherical gas distribution; the differences were not large compared to other uncertainties, such as the intensity of the $\sim 300\text{\AA}$ continuum.

E. Abundances and Dust

We assume solar abundances and a constant, uniform hydrogen density, with a filling factor of unity. Abundances are quite uncertain; however, tests show that changing the abundance of oxygen (several ionization stages of oxygen are major coolants in our model) by a factor of two from solar affects the iron coronal lines very little.

Several lines of evidence suggest that dust is underabundant in the diffuse gas. The X-ray column densities estimated by Mushotzky, Holt and Serlemetsos (1978) in NGC 4151 ($\geq 3 \times 10^{22}$ atoms per cm^{-2}) would imply a reddening due to dust of $A_V \geq 13$ mag given the Galactic dust-to-gas ratios, but the observed optical reddening is $A_V \leq 0.2$ mag (Wu and Weedman 1978). This discrepancy implies a dust-to-gas ratio of $\leq 1/200$ that of "normal", for the gas on the line of sight to the X-ray emitting region. The presence of normally refractory elements, such as iron, in the gas phase also suggests that depletion is not extreme. Sufficient iron must be present in its gas phase and not condensed onto grains (as is observed in the general ISM; Morton 1978) for the iron coronal lines to be present. It is easy to show, however, that our model continuum

does not destroy dust grains by sublimation in the coronal line emitting regions on any reasonable timescales (Draine and Salpeter 1979). It is possible that other dust destruction mechanisms are at work (see also Begelman 1985; Chang, Schiano and Wolfe 1987). Accordingly, we include the effects of dust, as discussed by Martin and Ferland (1980), assuming a dust-to-gas ratio 0.005 of Galactic, i.e., $\sigma_{\text{scat}}(V)/N_{\text{H}} = 2.5 \times 10^{-24} \text{ cm}^5$. This dust abundance is low enough to have little effect on the following calculations.

III. THE MODEL RESULTS

A. Coronal Line Intensities and Ratios

Given the assumptions outlined above, the only remaining free parameter is the hydrogen density, N_{H} (cm^{-3}), which we vary. The predicted line luminosities and ratios as a function of the hydrogen density are shown in Figure 53 and Table 14. These predictions are to be compared with Table 15, which summarizes observations of NGC 4151. In Table 15 we assume an [OIII] λ 5007 flux of $(1.19 \pm 0.06) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ (Antonucci and Cohen 1983; this was needed to normalize those line intensities which are given relative to [O III] λ 5007 in some studies). Table 16 lists the predicted relative strengths of other prominent lines for a density $N_{\text{H}} = 1.0 \text{ cm}^{-3}$.

Table 14

MODEL CORONAL LINE LUMINOSITIES AND LINE RATIOS

$\log [N_{\text{H}}(\text{cm}^{-2})]$	$\log (\text{Fe VII})$	$\log (\text{Fe X})$	$\log (\text{Fe XI})$	$\log \left(\frac{\text{Fe VII}}{\text{Fe X}} \right)$	$\log \left(\frac{\text{Fe XI}}{\text{Fe X}} \right)$	$\log \left(\frac{\text{Fe XIV}}{\text{Fe X}} \right)$	$\log \left(\frac{\text{Fe VII}}{\text{Fe XI}} \right)$
0.0.....	38.906	38.888	38.634	0.018	-0.254	-1.023	0.272
0.5.....	39.213	39.327	39.091	-0.114	-0.236	-1.009	0.122
1.0.....	39.513	39.723	39.487	-0.210	-0.236	-1.100	0.026

Table 15

IRON CORONAL LINE OBSERVATIONS OF NGC 4151

Line or Line Ratio	log (Line Ratio and Luminosity)	Reference
[Fe vii] 6087	39.92	Penston <i>et al.</i> 1984; Grandi 1978
	39.92	Boksenberg <i>et al.</i> 1975
	39.79	Osterbrock and Koski 1976
	39.80	Peterson <i>et al.</i> 1982
	39.86	OSU-unpublished
Mean	39.86 ± 0.06	
[Fe x] 6375	39.23	Penston <i>et al.</i> 1984
	39.53	Osterbrock and Koski 1976
	39.80	OSU-unpublished
Mean	39.52 ± 0.29	
[Fe xi] 7892	39.53	Penston <i>et al.</i> 1984; Grandi 1978
[Fe vii]	0.39 }	Penston <i>et al.</i> 1984; Grandi 1978
[Fe xi]	0.26 }	
Mean	0.33	
[Fe vii]	0.69	Penston <i>et al.</i> 1984
[Fe x]	0.27	Osterbrock and Koski 1976
	0.60	Pelat, Alloin, and Bica 1987
	0.53	Oke and Sargent 1968
	0.27	Souffrin 1968
	0.06	OSU-unpublished
Mean	0.40 ± 0.24	
[Fe xi]	0.30	Penston <i>et al.</i> 1984
[Fe x]	0.35	Pelat <i>et al.</i> and Grandi 1978
Mean	0.33	
[Fe xiv]		
[Fe x]	-0.12	Pelat <i>et al.</i>

Table 16

MODEL RELATIVE CORONAL LINE REGION LUMINOSITIES FOR AN
INTERSTELLAR MEDIUM DENSITY $N_H = 1.0 \text{ cm}^{-3}$

Ion (1)	$\lambda(\text{\AA} \text{ or } \mu\text{m})$ (2)	$L/L(\text{H}\beta)$ (3)
O vi	1035	3.605
Ly α	1216	23.018
O v	1218	1.392
N v	1240	0.670
C iv	1549	1.991
He ii	1640	2.386
C iii]	1909	0.145
[Fe xii]	2170	0.035
Mg vii	2629	0.192
Ne v	3426	0.972
H δ	4102	0.297
H γ	4340	0.505
He ii	4686	0.314
H β	4861	1.000
[O iii]	5007	7.271
[Fe xiv]	5303	0.008
[Fe vii]	6087	0.087
[Fe x]	6375	0.083
H α	6563	2.699
[Fe xi]	7892	0.046
[Si vi]	1.9 μm	0.172
[Mg v]	5.6 μm	0.784
[Ne vi]	7.6 μm	0.332
[S iv]	10.5 μm	1.707
[Ne v]	14.3 μm	0.200
[Ne v]	24.2 μm	0.371
[O iv]	26.0 μm	5.160
[Ne vii]	77.4 μm	0.114
[O iii]	88.0 μm	6.114
$\log L (\text{H}\beta) = 39.967$

Figure 53. Model results of the log of the luminosity (erg s^{-1}) of the $[\text{Fe X}]\lambda 6375$ line, and the log of the luminosity ratios $[\text{Fe VII}]\lambda 6087$, $[\text{Fe XI}]\lambda 7892$ and $[\text{Fe XIV}]\lambda 5303$ to $[\text{Fe X}]\lambda 6375$ and that of $[\text{Fe VII}]\lambda 6087$ to $[\text{Fe XI}]\lambda 7892$ as a function of the log of the hydrogen density in cm^{-3} .

The behavior of the line ratios shown in Figure 53 are the result of the interplay between changes in the mean ionization of the gas and the radial distribution of the ions. For a given ionization rate Γ (s^{-1}) and recombination coefficient α ($\text{cm}^3 \text{s}^{-1}$) (see Osterbrock 1988) the ionization balance between adjacent stages of ionization is simply

$$N^{i+1}/N^i \sim \Gamma/(N_H \alpha) \sim N_H^{-1} \quad (14),$$

so lower densities favor higher ionization. In Figure 53 the rapid decrease in intensity of lines from higher stages of ionization at higher densities is caused by the relatively low abundances of these ions.

The Strömgren radius R_S is also inversely proportional to density. For an extended geometry,

$$R_S \sim Q(H)^{1/3} N_H^{-2/3} \quad (15),$$

where $Q(H)$ is the number of hydrogen ionizing photons (Osterbrock 1988). As a result, the radial scale of the ionization structure shown in Figure 54 (for a density of $N_H = 1.0 \text{ cm}^{-3}$) also scales inversely with density. In the calculations the outer radius was held fixed, and as a result for densities much below $\sim 0.5 \text{ cm}^{-3}$ the [Fe VII] line is depressed because the Fe^{6+} zone occurs beyond the outer radius.

The relative coronal line intensities change little between densities of $\sim 0.5 \text{ cm}^{-3}$ and 10^3 cm^{-3} . Here, densities are low enough for all of the relevant stages of ionization to be populated, but yet high enough for all ionization stages to be within the fixed inner and outer radii. This insensitivity to density (the one remaining

parameter) is a major success for the present model. Figures 51 and 52 show both the incident (*solid line*) and transmitted (*dotted line*) continuum for two typical densities ($N_H = 0.5, 1.0 \text{ cm}^{-3}$). Objects which we view directly through the disk of the ISM will show moderate to extreme soft X-ray absorption. This presents a test of the model.

Given the uncertainties in some of the atomic physics and the difficulty in measuring these weak (usually a few percent of [O III] $\lambda 5007$) and sometimes blended lines, it is not surprising that there are some differences between Tables 14 and 15. One must note, however, that most of the predicted line luminosities and ratios of [Fe VII], [Fe X] and [Fe XI] all lie within a factor of 2 or 3 of the observed values. The small predicted [Fe XIV]/[Fe X] ratio is consistent with the fact that [Fe XIV] is rarely observed (see Osterbrock 1981, Pelat *et al.* 1987, Ward and Morris 1984 for possible observations of this line).

We emphasize again that we have not attempted to present a finely tuned model. One must keep in mind that our *mean* AGN model continuum was merely scaled to match the continuum intensity of NGC 4151 at 912Å. The strength and shape of the continuum in the $\sim 300\text{Å}$ and 100-400 eV regions is certainly important; however, we find that choosing different reasonable continua shapes (see, for example, Elvis 1987) does not produce qualitative differences. This simple model may be all that is necessary to produce the observed coronal lines in Seyfert galaxies.

Figure 54. The relative abundance of the four iron ions and the electron temperature as a function of distance from the central continuum source on a log-log plot for a hydrogen density of 1.0 cm^{-3} . The relative abundance of Fe^{13+} is represented by the dashed line, that of Fe^{10+} by the solid line, that of Fe^{9+} by the dotted line, and that of Fe^{6+} by the dash-dot-dash line. The electron temperature is indicated by the dash-triple dot-dash line.

B. The Size and Environment of the CLR

The model predicts that the CLR should be quite extended and spatially resolved in some cases. The distance ($R_{\max}$) from the central continuum source at which the coronal line emissivity is maximum, typical electron temperatures ($T_e[R_{\max}]$), and the effective emitting range (ΔR) (where the fractional ionization for ion is greater than approximately 10%) for different densities are shown in Table 17. Figure 54 shows, for one density, the electron temperature and ionization structures. The temperatures in the emitting regions are typical of nebular temperatures, and the emission regions span much of the NLR and perhaps beyond. The former result has been found to be true for at least [Fe VII] (Boksenberg et al. 1975, Osterbrock 1981, Fosbury and Sansom 1983), while the latter result should be observationally testable (spatially resolvable) for some of the more nearby Seyfert galaxies with strong coronal lines (NGC 4151, NGC 1068). Also note from Table 17 the size of the emitting regions - tens to hundreds of parsecs, and that there is some overlap in the emitting regions. Coronal line variability is then another observational test of the model; the coronal lines should not vary over timescales of a month to a year (see Veilleux 1988a), due to the extended nature of the emitting region. For reasons discussed above, the higher ionization stages tend to occur at smaller radii and over smaller ranges. As one might expect, [Fe VII] and [Fe X] have the largest $R_{\max}$ and would therefore be easiest to test the extendedness of the CLR. $R_{\max}$ is independent of the geometry we use and is mainly dependent upon the number of ionizing/exciting photons and electron density.

Table 17

TYPICAL ELECTRON TEMPERATURES, RADII, AND EFFECTIVE EMITTING RANGES
AT MAXIMUM EMISSIVITY

Ion	$\log [N_H(\text{cm}^{-3})]$	$T_e(R_{\text{max}})$	$R_{\text{max}}(\text{pc})$	$\Delta R(\text{pc})$
Fe vii	0.0	16,000 K	1200	745-1400
	0.5		610	350-660
	1.0		290	210-300
Fe x	0.0	26,000 K	420	200-750
	0.5		245	110-415
	1.0		130	75-200
Fe xi	0.0	28,000 K	350	130-520
	0.5		200	85-290
	1.0		110	45-160
Fe xiv	0.0	70,000 K	145	80-200
	0.5		85	45-140
	1.0		45	25-70

Several other lines are predicted to be strong. See Table 16. The [Fe XII] λ 2170 line is predicted to be typically ~ 40% or so of [Fe X] λ 6375, although confirmation of this line and its strength will probably have to await the Hubble Space Telescope (HST). The model predicts that the CLR produces significant [Ne V] λ 3426 emission, typically ~ 12 times the strength of the [Fe X] line. Extended [Ne V] emission is sometimes seen (Ward 1988). Many of the other lines given in Table 16 are also produced in the NLR, so it would be difficult to test those predictions observationally.

*C. A Possible Coronal Line Region, Extended Narrow-line
Region, and Radio Jet Connection*

The orientation of the radio jet relative to the galactic disk may be important in determining the strength of the coronal line region. In two galaxies where an ENLR has been observed and the radio jet lies within the galactic disk in the direction of the ENLR (NGC 4151, NGC 1068) (Wilson and Ulvestad 1982; Heckman and Balick 1983; Unger *et al.* 1987, 1988; Schulz 1988), strong coronal lines are observed (Penston *et al.* 1984). In NGC 4388, in which extended (non-coronal line) emission due to the Seyfert nucleus is observed above and below the galactic disk, the radio jet lies along the direction of the ENLR but perpendicular to the galactic disk, and at least [Fe X] λ 6375 is very weak or absent (Corbin, Baldwin and Wilson 1988; Filippenko and Sargent 1985; Shields 1988); the other coronal lines have not been well studied. In all three cases the ENLR lies in the direction of the radio jet which may represent the escape route of the nuclear radiation exciting the CLR

and ENLR, but the coronal lines appear to be strong only when the radio jet lies in the galactic plane. It is possible that there is insufficient ISM being hit by the Seyfert nucleus, if it is preferentially "beamed" perpendicular to the galactic disk, to produce strong coronal lines, in objects where the radio jet does not lie within the disk. This is consistent with our model, and may be evidence that the radio jet or inner radio structure, an anisotropic nuclear radiation field, the CLR and the ENLR are all in some way interconnected. If so, then this may tell us something about the distribution of material within the inner few parsecs of the centers of these AGN. For example, did the $\sim 4''$ nuclear radio jet of NGC 4151 punch a hole through any obscuring gas, allowing radiation to escape to large distances? It may be that the anisotropy of the nuclear radiation may be due to a dense obscuring torus (as in Antonucci and Miller 1985) whose axis coincides with the radio axis. In the most recent studies of the ENLR of NGC 4151, Perez-Fournon and Wilson (1990) find this unlikely, since in the case of NGC 4151 the torus would also obscure our view of the BLR as well, which is not the case. It is also possible that the ENLR and CLR are truly seeing the "bare AGN engine", e.g., a geometrically thick radiation-supported accretion torus, which collimates the radio jet, surrounding a supermassive black hole that powers the jet. Acosta Pulido *et al.* (1990) find that models of the emission line spectra of the ENLR based upon photoionization by such accretion disks can constrain the mass of the supermassive black hole and the size of the accretion disk. The results of our model for the origin of the coronal lines could surely help in this respect.

In recent years large amounts of observational evidence has been amassed supporting the picture that the ENLR in Seyfert galaxies is excited by a bare anisotropic Seyfert radiation field and lies along the direction of a nuclear radio jet (see, for example, Heckman and Balick 1983; Unger *et al.* 1987, 1988; Corbin, Baldwin and Wilson 1988; Schulz 1988; and references therein). The coronal line region should also see a bare Seyfert nucleus. Thus another observational test is the predicted relationship between the CLR and the ENLR; i.e. does the CLR lie along the same direction as the ENLR, implying that the CLR has a clear view of the Seyfert nucleus? If the ENLR and the CLR are indeed seeing the same bare Seyfert nucleus, then in principle an upper-limit to the warm-phase ISM density in the direction of the ENLR and thus that in the CLR can be established.

D. Soft X-ray Extension

A final result of our model is that the predicted Compton scattering optical depths are sufficient to explain the extended soft X-ray emission observed by Elvis, Briel and Henry (1983) in NGC 4151 as simply nuclear X-rays scattering off the coronal line gas. The optical depth to electron scattering (radially) through the disk is

$$\tau_{es} \approx 0.005(1.0\text{cm}^3 N_H) \quad (16).$$

This relation holds while the gas is fully ionized; an ionization front occurs when $N_H \approx 4 \text{ cm}^{-3}$; then $\tau_e \approx 0.020$. We expect this medium to scatter a fraction $(1-e^{-\tau}) \sim \tau$ or a few percent of the incident radiation field. This is sufficient to explain the observed soft X-ray

extension in NGC 4151 as simply scattered *unextinguished* nuclear continuum. The intrinsic soft X-ray continuum, extrapolated from the hard X-ray observations of Holt *et al.* (1980) assuming no extinction, amounts to $\sim 1.7 \text{ counts s}^{-1} \text{ keV}^{-1}$ at 0.5 keV. The CLR will scatter $\sim 1\%$ of this (depending on the density), and this is sufficient to account for the less than or equal to 30% *extension* contribution to the *total* soft excess component flux observed in NGC 4151 (Elvis, Briel and Henry 1983; Perola *et al.* 1986; Pounds *et al.* 1986). One might then expect that other Seyfert galaxies exhibiting ENLRs and CLRs that lie in the disk of the galaxy to have extended soft X-ray regions as well; we just have not been able to resolve them.

E. Kinematics and Linewidth

The model does not attempt to explain the structure or kinematics of the coronal line emitting region; there are some indications that at least the [Fe VII] lines arise from multiple components (and plausibly multiple mechanisms) in some Seyfert galaxies. These lines show large blueward asymmetries in at least one Seyfert galaxy (Mrk 359) in the sample studied by Veilleux (1988b). Our calculations, and others, suggest that [Fe VII] also has a contribution from the NLR, so several regions are expected to contribute to the net profile of this line.

As a further complication, it can be shown that the nuclear continuum can radiatively accelerate the low density gas, in the presence of *some* dust, to large velocities ($\sim 10^3 \text{ km s}^{-1}$) over distances of order the CLR. The major uncertainty in this is the actual amount of dust present in the ISM. If an appreciable fraction of the carbon is in

graphite in the CLR, then effective radiative acceleration is inevitable, so that the coronal line widths will not reflect the rotation velocity of the galaxy. Further dynamical considerations along these lines are presented by Chang, Schiano, and Wolfe (1987).

IV. CONCLUSIONS

This paper presents calculations examining the effects of a bare Seyfert galaxy continuum on the surrounding interstellar medium. These calculations show that high-ionization lines are produced, with relative intensities quite similar to those observed. The line strengths and ratios show a basic insensitivity to density. In this picture the observed soft X-ray extension is the result of electron scattering off the ISM. This model is open to several observational tests. These are the following.

1. *Spatial Extent*.---We predict the coronal line region to lie at or beyond the narrow-line region, in a direction with an unobscured view of the nucleus. Thus it should be resolvable, at least for nearby objects. The resolved CLR should lie in the same direction as the extended NLR emission and radio emission. The CLR could provide a mechanism to map the anisotropic radiation field of the nucleus.
2. *Variability*.---The high ionization lines should not be variable. Variability over timescales of a month to a year would require that the bulk of the gas be closer to the nucleus than we predict (see Veilleux [1988a] for a recent variability study). However, we do predict that the CLR should lie over an angular extent of several to ten seconds of

arc for some of the nearby Seyfert galaxies. Typical entrance apertures are often of order this size, so that small centering errors can effect the line strengths. Very large apertures and careful centering are needed to measure these line strengths reliably. Long exposure, small (0.25 arcsecond) aperture *HST* observations centered on the nucleus of some nearby Seyfert galaxies with strong coronal lines might be a test for their presence in the so-called transition line region (i.e., the compact hypothesis). If the coronal lines are present at full strength in such observations, then the extended hypothesis, presented here, can be ruled out.

3. *Kinematics*.---The line profile, produced by the gas we model, should characterize low density gas at large radius. We do not address kinematics or the observed coronal line profiles in this paper. However, it has been shown (Chang, Chiano and Wolfe 1987) that radiative acceleration of the host galaxy ISM due to the AGN continuum is significant, and might, therefore, contribute to the dynamics of the coronal line emitting region. Given the complexity of the AGN phenomenon, it would be surprising if other gas, perhaps at smaller radii, did not also exist. High spectral resolution, high signal-to-noise, spatially resolved observations will provide a decisive test of this model.

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CHAPTER VI

SUMMARY OF MAJOR RESULTS AND FUTURE WORK

Broad Line Flux Variability in HLAGN.---Broad emission line flux variability on timescales less than one year was found for 1 and possibly 3 radio quiet QSOs. These results and those of several LLAGN continuum and broad emission line flux monitoring campaigns are certainly suggestive of small BLRs in HLAGN as well. If we can better estimate the sizes of the BLRs in HLAGN, then we may test the validity of the rather curious $R_{\text{BLR}} \propto L^{0.5}$ scaling law implied by the single ionization parameter standard model, where L is the ionizing luminosity of the central continuum source. It has never been clear how the BLR gas could arrange itself such that it always has nearly the same ionization parameter over a huge range ($\sim 10^4$) in the continuum luminosity. However, further studies such as this one are needed to establish what temporal sampling would be sufficient in future monitoring programs to investigate the size and structure of the BLRs in these AGN. Patience and good fortune are requirements for such programs, as broad emission line variability in the radio quiet AGN is apparently not common.

Broad Emission Line Profile Variability in Akn 120.---First, it was found that broad permitted Fe II emission can account for the "red shelf" of H β , as well as some of the structure and variability of the H β profile. Second, the broad emission line profiles are complex and highly variable. The mechanism for the change in profile is unknown, but the timescale for change is short (< 5 months). Single component models for the BLR in this Seyfert galaxy are unlikely. If the component profiles do not deviate greatly from Gaussian, then no fewer than 4 components are required to describe the Balmer broad line profiles. Third, we pointed out the dangers of interpreting difference spectra and the results of profile fitting, especially under the conditions of low S/N ratios (< 100), low spectral resolution (worse than $\sim 5\text{\AA}$), and poor temporal sampling. Fourth, again patience and good fortune are requirements. As our experience with Akn 120 shows, these objects can and do vary when we are not observing them, and sometimes do nothing when we are.

A profile analysis complementing the determination of the transfer function with high quality data, in which changes in the broad line fluxes and profiles are time-resolved, is required to properly investigate the structure of the broad line emitting regions in AGN. This must be done for a number of broad emission lines, covering a wide range of excitation energies and emission mechanisms. This has already been done, to some extent, for NGC 5548 in the recent optical and ultraviolet monitoring campaign, although the UV data and some of the optical data may be of too low quality for much useful profile analyses.

If the structure of the BLRs in NGC 5548 and Akn 120 become well constrained or, better yet, "solved", it will be a great leap toward understanding the wide diversity in the broad emission line profiles. While the broad emission line profiles in some AGN are similar to those in the above mentioned AGN (e.g., Mrk 79 and Mrk 279), in many cases they are very different. For example, the broad emission line profiles in some Seyfert galaxies and BLRGs are smooth and triangular, unlike those four Seyfert 1 galaxies mentioned above. There is a tendency for the radio loud AGN to have rectangular, flat-topped, or otherwise very lumpy profiles, while the higher luminosity radio quiet AGN tend to have more regular profiles as compared to the Seyfert galaxies. These differences in the broad emission line profiles may be related to the nature of central engines of these AGN.

Broad Emission Line Profile Variability in Mrk 590.---An enormous change in the broad Balmer emission line profiles occurred between two observations in which the optical continuum changed by a factor of 4. The profile variation revealed two components, a relatively narrow core which changed in flux and a very broad base which apparently did not. The broad Balmer emission line cores had almost disappeared in the low state! We identified the variable core with the classical BLR and the very broad base with a new region which lies between the BLR and the central continuum source, an optically thin VBLR. The VBLR was modeled with a photoionization code and we discovered that such gas can explain a number of phenomena of AGN. First, it can account for the very broad bases of the Balmer lines and a variety of high excitation lines

observed in a number of AGN. The optically thin VBLR can also account for the narrow resonance line absorption and the soft X-ray absorption which are observed in generally the LLAGN, and the inferred soft ionizing continua of Seyfert galaxies. Furthermore, the VBLR gas is a source of free-free emission which can account for the big blue bump and the centimeter excess observed in radio quiet AGN. Better temporal coverage of this object will be needed to confirm our hypothesis that the very broad base is optically thin to the ionizing continuum, and the identification of a *non-varying* Balmer VBL component in other AGN broad Balmer line profiles would provide further support for the model. Contemporaneous optical, ultraviolet, and X-ray measurements are needed to place further constraints on the model. Such observations are about to be made with *IUE* and *ROSAT*. In addition further modeling needs to be done with a more realistic "intrinsic" AGN continuum incident to the VBLR in order to better examine the "filtered" continuum that is incident to the BLR and its effects on the BLR gas.

As a final note to all studies of broad emission line variability, we still do not really know the spectral energy distribution or behavior of the ionizing continuum. It has been assumed that it is strictly correlated with the *IUE* ultraviolet. This might be true of the Lyman continuum, but the extreme ultraviolet may be and the soft X-rays are almost certainly doing something different. We can never expect to understand the BLR without first understanding the region of the spectrum that is energizing it. As noted in Chapters I and IV, the behavior of the BLR and VBLR emission lines may be a predictor of the

spectral energy distribution and behavior of the ionizing continuum. However, this is true only to the extent that we understand the emission processes within these regions. In fact, as implied by the results of Chapter IV, we cannot fully understand either the ionizing continuum or line emitting regions independent of each other. We suggest the following as steps toward understanding the AGN phenomenon. First, as a short-term goal the future broad emission line monitoring programs should include at least a few observations in as many regions of the ionizing continuum that are accessible. Sometime in the near future *ROSAT*, *EUVE*, and *LYMAN* may allow for such observations. However, we need to know how the various wavebands in the continuum are behaving when the broad emission lines are quiescent as well as when they are varying to determine how the the different continuum wavebands are related to each other and to the broad emission lines. The continuum, too, is believed to be composed of multiple emitting components. Thus, step two, we will eventually need a dedicated multiwavelength (satellite) observatory to monitor simultaneously the emission lines and continuum in AGN in as many wavebands as possible, including the infrared and radio. It must be capable of sampling a wide range in AGN luminosity.

The Coronal Line Region.---We presented the most detailed calculations on the origin of the coronal emission lines in AGN to date. In this model we hypothesize that the same anisotropic nuclear ionizing radiation (i.e., the AGN central continuum source) that is exciting H II region type clouds ($N_e \sim 10^2 \text{ cm}^{-3}$) at distances of $\sim 1 \text{ kpc}$ (i.e., the

ENLR) also excites the lower density interstellar medium ($N_e \sim 1 \text{ cm}^{-3}$) to emit the high excitation coronal lines. Thus in this model the coronal line region ought to be extended, lying a few to several arcseconds from the nucleus in some nearby Seyfert galaxies, and along the same direction as the ENLR. One of the most important characteristics of our model is its simplicity. If ionizing radiation from the central continuum source is present with the warm phase ($N_e \sim 1 \text{ cm}^{-3}$) ISM, and the ENLR emission line ratios suggest that it is, the high excitation coronal lines should result. In addition the coronal line gas may also be responsible for the observed extended soft X-ray sources (now observed in 3 Seyfert galaxies), through electron scattering of the nuclear AGN continuum. Several observational tests of our model were given.

We also noted that a high resolution spectrum of the $[\text{Fe VII}]\lambda 6087$ profile in one Seyfert galaxy reveal possible multiple emission components, just as for the broad line profiles. This certainly complicates the picture. However, unlike the case for the BLR, constraining the structure of the CLR through observations is somewhat more straightforward, at least in as much as determining whether the CLR is compact, extended or both.

Finally, we would like to determine why and on how small a scale the AGN continuum is anisotropic. As mentioned in Chapter II, this could have important implications to the studies of the BLR structure. The study of the spatially resolved emitting regions in AGN (NLR, ENLR, and CLR) may provide us with clues.

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Non-Cosmetic errors/corrections for Ph.D. thesis by K.T. Korista (1990)

CHAPTER 2:

0514-001 should be 0514-005 (throughout thesis).

CHAPTER 3:

bottom of p43, last sentence: should be "Section IV", not Section I.

bottom of p62, last sentence: should be "Equation 4", not Equation 2.

middle p77, second sentence of first whole paragraph: delete "(minus the Fe II shelves)".

p84, section b., third sentence: "...that closely corresponds IN FLUX to our data..."; add the capitalized text.
(we had H-beta data (JD 2445208,5231) contemporaneous with the ABP88 data, but they were of unusually low quality (S/N) and I did not include them in the thesis. We had no H-alpha data of similar flux state near the epoch of the ABP88 observations. Thus I chose JD 2444615, another very high flux state for which we had both lines for comparison.)

p95 = Table 8, experiment 3 in the flux column: for JD 2447582 data and the 4886.2A component the flux should read 5.41 (not 4.63).

p112, second sentence: should read "The timescale for broad LINE CLOUD collisions is...."; the order of the capitalized words was reversed.

p115 just above equation 10: "...roughly the cooling time of the gas IN THE SHOCKED REGION:...."; add the capitalized words.