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AN ANALYSIS OF THE BROAD EMISSION LINE PROFILES OF SEYFERT 1 GALAXIES

The Ohio State University

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An Analysis of the Broad Emission Line Profiles of Seyfert 1 Galaxies

DISSERTATION

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

By

Daniel Michael Crenshaw, B.S.

* * * * *

The Ohio State University

1985

Reading Committee: Approved By

Dr. Eugene R. Capriotti
Dr. David G. Lawrie
Dr. Bradley M. Peterson

Bradley M. Peterson, Adviser
Department of Astronomy
DEDICATION

To Jo
ACKNOWLEDGEMENTS

This dissertation would not have been possible without the guidance of my adviser, Professor Bradley M. Peterson. I would like to thank Professor Peterson for his original suggestion of the main topic of this dissertation, and for his valuable comments and advice on various aspects of this work. I would like to thank Professor Eugene R. Capriotti, for his helpful suggestions and encouragement throughout the course of my research on this topic. I am also indebted to Professor David G. Lawrie, for his suggestions and comments concerning earlier drafts of this manuscript.

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Finally, I would like to express my gratitude to my wife, Jo, for her constant love and support. I am particularly proud of her own academic success, which she attained despite many sacrifices made on my behalf.
VITA

March 16, 1957 ... Born - Rock Hill, South Carolina

1979 ... B. S., Georgia State University, Atlanta, Georgia

1979 - 1982 ... Teaching Associate, Department of Astronomy, The Ohio State University, Columbus, Ohio

1982 - 1983 ... Research Assistant, Department of Astronomy, The Ohio State University, Columbus, Ohio

1983 ... Lowell Observatory Summer Fellow, Lowell Observatory, Flagstaff, Arizona

1983 - 1984 ... Perkins Research Assistant, Department of Astronomy, The Ohio State University, Columbus, Ohio

1984 - 1985 ... Teaching Associate, Department of Astronomy, The Ohio State University, Columbus, Ohio

PUBLICATIONS


**ABSTRACTS**


**FIELDS OF STUDY**

**Major Field:** Astronomy

Studies in Seyfert 1 Galaxies and QSOs.  
Professors Bradley M. Peterson and Eugene R. Capriotti

Professor Bradley M. Peterson

Studies in Early- and Late-Type Stars.  
Professors Arne E. Slettebak and Phillip C. Keenan
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Chapter I
INTRODUCTION

Seyfert galaxies have extremely bright nuclei that show signs of strong activity. Although Seyfert galaxies were first identified in the early 1940s (Seyfert 1943), their importance was not recognized until decades later when their similarity to quasars, the brightest known objects in the universe, became apparent. In 1963, Maarten Schmidt found that the spectra of quasars are highly redshifted. He realized that if quasars are at the distances implied by their redshifts, their luminosities in some cases must exceed those of the brightest known galaxies by several orders of magnitude. However the rapid variability of some quasars suggests that the continuum source, which is responsible for most of the emitted radiation, can be smaller than a few light-days in size. Even though much progress has been made, the basic process by which so much radiation is emitted from such a small volume of space is still not understood.

Soon after Schmidt's discovery it was realized that the nuclei of Seyfert galaxies are very similar to many qua-
Seyfert nuclei and similar objects, including quasars, are now grouped together into one class of objects known as active galactic nuclei (AGN). Known Seyfert galaxies are much closer to us than known quasars, and therefore they are much brighter in apparent magnitude on average. Thus the importance of Seyfert galaxies is that they provide us with an opportunity to investigate the basic physical processes occurring in AGN with even moderate aperture telescopes.

On the basis of spectroscopy, Seyfert galaxies can be divided into types 1 and 2 (Khachikian and Weedman 1974). Seyfert 1 galaxies have optical spectra that consist of four distinct components:

1. A nonthermal continuum normally contributes most of the total light in small apertures and is well fit by a power-law, $F \propto \nu^{-\alpha}$ (where $\alpha$ is typically in the range 1.0 to 1.5), at wavelengths between 4000 Å and 8000 Å (in the rest frame of the galaxy).

2. A contribution from the host galaxy, consisting primarily of a stellar continuum and stellar absorption features, may be significant if the nonthermal continuum luminosity is rather low.

3. Broad emission lines with typical full widths at zero intensity of order $10^4$ km s$^{-1}$ are present. The broad-line region (BLR) is thought to contain clouds of
emitting gas traveling at high speeds and is probably 0.1 pc or less in size. The lack of strong [O III] \( \lambda \lambda 4959, 5007 \) emission from this region and the observed strength of C III] \( \lambda 1909 \) emission in the ultraviolet suggests that the electron density in a cloud is somewhere in the range \( 10^6 \) to \( 10^{10} \) cm\(^{-3} \) on average.

4. Narrow emission lines with typical full widths at zero intensity of order \( 10^{3} \) km s\(^{-1} \) are present. The narrow-line region (NLR) is also thought to contain clouds of gas traveling at somewhat lower speeds and is likely to be \( 10^{2} \) to \( 10^{3} \) pc in size. NLR clouds are characterized by much lower densities in the range \( 10^{3} \) to \( 10^{6} \) cm\(^{-3} \).

The main difference between the two types of Seyferts is that Seyfert 2 galaxies lack the broad emission lines discussed above, although other differences exist as well (Weedman 1977; Osterbrock 1978a).

This dissertation is a study of the optical spectra of Seyfert 1 galaxies; in particular we will concentrate on the broad emission lines and their profiles. One of the most basic unanswered questions concerning the BLR is: What is the velocity distribution and emissivity of the BLR gas as a function of position relative to the nonthermal continuum source? Specifically, is the BLR gas undergoing
gravitational infall, radiatively-driven outflow, outflow due to an explosive event, turbulence, rotation, or some other type of motion? An answer to these questions will provide clues to the nature of the nonthermal continuum source, since it probably dictates the dynamics of the BLR.

Although we do not know the answers to the above questions, we do know that photoionizing radiation from the nonthermal continuum source provides the energy necessary to produce the emission lines in both the BLR and NLR. Early photoionization models were fairly successful in explaining the observed broad-line ratios until the discovery by Baldwin (1977) of the "La/Hβ problem". Baldwin finds from a composite spectrum of low- and high-redshift quasars that La/Hβ = 3, a factor of 10 lower than predicted by models. Subsequent studies (Wu, Boggess, and Gull 1983) find that for Seyfert 1 galaxies La/Hβ = 5 on average.

Recent photoionization models (Kwan and Krolik 1981; Weisheit, Shields, and Tarter 1981) are much more successful in matching the observed La/Hβ ratios and the other strong optical and ultraviolet relative line intensities. These new models consider a BLR cloud which is very optically thick to ionizing radiation at the Lyman limit. As in the earlier models, the continuum radiation produces an HII zone in which most of the cooling is done by the ultraviolet lines La, C IV λ1549, C III] λ1909, and O VI λ1034.
The improvement to earlier models is due to the realization that continuum X-rays penetrate further into the cloud past the HII zone to create a partially ionized zone (PIZ) in which approximately 10 - 20% of the hydrogen is ionized. Due to the large La optical depths in the PIZ, a significant amount of hydrogen is maintained in excited states. Most of the cooling in this zone is done by collisional excitation of the Balmer lines and MgII λ2798, and by Balmer continuum emission. The Hβ flux in particular is enhanced by a factor of 5 to 10 and thus the La/Hβ problem is resolved.

Our understanding of the kinematics of the BLR is much less satisfactory; we still do not know if gravity, radiation pressure, or wind pressure is the dominant force in the BLR. Although detailed kinematic models exist and various arguments have been made for and against these models, we apparently do not have enough information at present to prove if any given model is the correct one. For example, the functional form of individual line profiles, which is logarithmic in many cases, is not sufficient to distinguish among many models. Capriotti, Foltz, and Byard (1980) show that several cases of spherically symmetric radial motion can result in logarithmic profiles. Also, van Groningen (1983) claims that many of the observed profiles are similar to profiles produced by a turbulent rotating disk.
Studies of the time-delayed response of the broad-lines to changes in the nonthermal continuum flux may eventually help us understand the BLR kinematics (Blandford and McKee 1982; Capriotti, Pultz, and Peterson 1982). This technique should be effective for Seyferts in which the light-travel time across the BLR is of the same order of magnitude as the time scale for significant continuum changes to occur (Peterson, Crenshaw, and Meyers 1985). A large amount of high-quality data must be accumulated however before we can determine if variability studies are the key to understanding the BLR kinematics.

If the physical conditions and the cloud velocities both change in a systematic fashion across the BLR, then emission lines such as Hα, Hβ, and He I $\lambda$5876 should have different profiles. Thus another possible way to probe the BLR kinematics, as discussed by Shuder (1982, 1984), is to compare the profiles of different emission lines. Shuder does this by dividing one profile by another, point by point, to obtain line ratios as a function of radial velocity. Since the "profile ratios" for individual objects are rather noisy, he averages them by normalizing the velocity scale in each object to the full width at zero intensity of Hα in that galaxy. Shuder finds that the average Hβ/Hα ratio increases by a factor of 2.2 from the core to the wings, whereas the average He I/Hα ratio increases by a
factor of 5 from the core to the wings. Recent photoionization model results from Kwan (1984) demonstrate that both these ratios increase with the ionizing flux incident on a BLR cloud; thus the ionizing flux apparently increases with velocity. These results place an important restriction on kinematic models: clouds closer to the continuum source must have higher velocities on average.

Our first objective in this dissertation is to test the results of Shuder by determining if the intrinsic Hβ/Hα ratio really does increase with radial velocity in most Seyfert 1 galaxies. For example, if the intrinsic profiles are identical, then any contamination effect which makes the observed Hβ profile have a weaker core or broader wings than the observed Hα profile will cause the observed Hβ/Hα ratio to increase with radial velocity. Therefore we consider three effects not considered by Shuder which, if not corrected for, weaken the core or strengthen the wings of the Hβ profile relative to the Hα profile:

1. We will demonstrate that contamination of the broad emission lines by stellar absorption features lowers the peak of the Hβ profile in Seyferts with low nuclear luminosities.

2. A shelf of emission is often seen in the red wing of the Hβ profile which is not intrinsic to Hβ. Although Shuder removes the Fe II that contributes to the
shelf, an additional component (probably broad [O III]) exists as well.

3. The velocity resolution for Hβ is worse than that for Hα. The observed Hβ profile therefore has a weaker core than it would have if its resolution were the same as that of Hα.

Even after correcting for the above effects, we find that Hβ/Hα increases dramatically with radial velocity in basic agreement with Shuder's results. This suggests additional motivation for this study. Photoionization models have reached the stage of sophistication where they can now be combined with different kinematic models to produce not only single profiles, but profile ratios as well. Thus we will provide high signal-to-noise profile ratios so that they can be compared in the future with results from these models in the hope that they will provide additional constraints on the kinematics of the BLR. We will also investigate the dependence of the profile ratios on the luminosity of the nonthermal continuum and the width of the broad emission lines. Finally we will use the photoionization model results of Kwan (1984) to put restrictions on the size and geometry of the BLR.

In Chapter II we give the details of the observations and data reduction procedures. In Chapters III and IV we discuss the contamination of the broad-line profiles by
stellar absorption features and emission features from the BLR and NLR, and give the procedures we use to correct the profiles. We present the decontaminated profiles and profile ratios in Chapter V and Appendixes A and B. Finally, we discuss our interpretation of the profile ratios in Chapter VI.
Chapter II
OBSERVATIONS

2.1 INSTRUMENTATION

We have observed twelve Seyfert 1 galaxies in order to study the profiles of the broad emission lines. The observations were made with the Ohio State University image dis-sector scanner (IDS) on the Perkins 1.8-m reflector of the Ohio Wesleyan and Ohio State Universities at Lowell Observatory. The IDS is a dual-beam spectroscopic scanner that allows simultaneous observations of an object and the sky. The linear response of the IDS over a large dynamic range makes it a useful tool for studying the spectra of Seyferts.

The design of the IDS is very similar to that of the Lick Observatory scanner (Robinson and Wampler 1972). An optical layout and detailed description of the spectrograph is given by Byard et al. (1981). The most important component of the IDS is a chain of three 40 mm S-20 extended-red electrostatic Varo image tubes, which increase the gain by a factor of $\sim 10^5$ and provide temporary storage of the photon events. The output phosphor of the last image tube is
scanned by an ITT image dissector. Since each photon event is counted more than once and the number of counts per photon varies, the counts are not distributed according to Poisson statistics and the signal-to-noise is more difficult to determine than with a photon counting device.

An IDS spectrum is stored in a file on disk in the form of counts per channel. Each spectrum consists of 2046 channels, and the number of counts in each channel can range from 0 to 32,767. Usually an observation of a particular object will generate a number of files which can be combined at a later date.

Since this is a profile study, it is important to know the properties of the instrumental profile, which is approximated well by the profile of an emission line from an iron neon hollow cathode. The instrumental profile is fit well by a Gaussian from its peak to the point at which the emission is \( \sim 3\% \) of the peak; in the far wings however the profile rises above a Gaussian. The resolution can be characterized by the full width at half maximum (FWHM) of the instrumental profile. The resolution over a red scan (defined in the next section) as a function of channel position is shown in Figure 1. As can be seen in Figure 1, the resolution is 5-6 channels in the middle half of the scan and degrades rapidly at the ends of the scan. To get optimum resolution therefore, it is necessary to choose the
wavelength coverage so that the broad-line profiles of interest are not near the extreme ends of the scan.
Figure 1: Resolution as a function of channel position.
2.2 OBSERVATIONAL PARAMETERS

All of the IDS scans were taken with a 600 lines mm\(^{-1}\) grating blazed at 5500 Å in first order. Circular apertures of projected diameter 5" or 7" were used to reduce the effects of atmospheric refraction and to get an estimate of absolute fluxes. The resolution in the middle of the scans for this grating is \(\approx 7\) Å with the 5" apertures and \(\approx 9\) Å with the 7" apertures. A blue scan centered near 5200 Å and a red scan centered near 6800 Å were obtained to provide coverage of each Seyfert from 4000 Å to 8000 Å and to insure that the profiles of Hα and Hβ were near the center of the scan. The region of overlap for the blue and red scans spans 600 - 800 Å and contains the He I \(\lambda 5876\) profile.

The integration time per individual scan was limited to 300 - 600 s to minimize the effects of variable sky brightness, image tube afterglow, and changes in the extinction. The total integration time in the blue or red required to obtain high signal-to-noise in the continuum of each Seyfert ranged from 1 to 3 hours. Since the broad emission lines of most Seyfert 1 galaxies are variable over timescales of months or years (Peterson et al. 1982, 1984, 1985) the blue and red observations were made within days of each other.

The only criteria for inclusion of a Seyfert 1 galaxy in this study are that (1) it is bright enough to yield high
signal-to-noise data and (2) its Fe II emission is not so strong that it severely contaminates the other broad-line profiles. A journal of our observations is presented in Table 1.
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<td>4100–6500</td>
<td>10800s</td>
<td>7&quot;</td>
</tr>
<tr>
<td></td>
<td>1984 Jan 5</td>
<td>5800–8200</td>
<td>6600s</td>
<td>7&quot;</td>
</tr>
<tr>
<td>Mrk 110</td>
<td>1984 Jan 2,4</td>
<td>4100–6500</td>
<td>12600s</td>
<td>7&quot;</td>
</tr>
<tr>
<td></td>
<td>1984 Jan 5,7</td>
<td>5800–8200</td>
<td>6000s</td>
<td>7&quot;</td>
</tr>
<tr>
<td>Mrk 335</td>
<td>1983 Sept 11</td>
<td>4000–6400</td>
<td>7200s</td>
<td>5&quot;</td>
</tr>
<tr>
<td></td>
<td>1983 Aug 31</td>
<td>5600–8000</td>
<td>6000s</td>
<td>5&quot;</td>
</tr>
<tr>
<td>Mrk 509</td>
<td>1983 Sept 14</td>
<td>3900–6500</td>
<td>6000s</td>
<td>7&quot;</td>
</tr>
<tr>
<td></td>
<td>1983 Sept 16</td>
<td>5700–8300</td>
<td>4800s</td>
<td>7&quot;</td>
</tr>
<tr>
<td>Mrk 590</td>
<td>1983 Oct 13</td>
<td>4000–6400</td>
<td>8400s</td>
<td>7&quot;</td>
</tr>
<tr>
<td></td>
<td>1983 Oct 12</td>
<td>5600–8400</td>
<td>10200s</td>
<td>7&quot;</td>
</tr>
<tr>
<td>3C 120</td>
<td>1983 Dec 5</td>
<td>3900–6300</td>
<td>9000s</td>
<td>7&quot;</td>
</tr>
<tr>
<td></td>
<td>1983 Dec 7</td>
<td>5700–8100</td>
<td>8400s</td>
<td>7&quot;</td>
</tr>
</tbody>
</table>
2.3 DATA REDUCTION

The reduction of our IDS data involves converting the observed counts as a function of channel to flux units (ergs s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\)) as a function of wavelength (Å). We reduced all of our data on the PDP 11/34 computer of the Department of Astronomy at Ohio State University using the Interactive Reduction System discussed by Jenkner (1980). The following procedures are performed for each 300-600s object scan from a given aperture:

1. Subtract the night-sky scan (taken immediately before or after the object was observed) from the object scan. To a good approximation, the image tube after-glow from the object is also removed by this subtraction.

2. Divide by the exposure time to get the count rate per channel for the object.

3. Divide by a flat field scan (from a quartz-halogen lamp) to remove channel-to-channel sensitivity variations of the image tubes.

4. Apply a dispersion-curve fit (determined from a scan of an iron neon hollow cathode) to the scan to convert channel position to wavelength.

5. Correct for atmospheric extinction using the mean extinction curve determined by Tug, White, and Lockwood (1977) for Lowell Observatory.
6. Remove the telluric A and B absorption bands in the red scan created by the atmosphere by using the procedure described by Cota, Wagner, and Newsom (1985).

The above steps are repeated for each object scan. All of the scans for a particular aperture are then averaged and the following steps performed:

1. Shift the zero-point of the dispersion curve to correct for any small (always < 5 Å) shift of the object scans relative to the iron neon scan in the dispersion direction. The zero point shifts are determined by comparing the laboratory wavelengths of the atmospheric emission lines [O I] λλ5577.3, 6300.3 to their observed wavelengths.

2. Resample the data to linearize the wavelength scale.

3. Multiply by a calibration array to convert counts to flux units. The calibration array is determined by observing standard stars, performing the above reduction procedures on them, and comparing the resulting spectra to the fluxes determined by Stone (1977) for these stars.

The east and west aperture data are reduced separately and are independent observations of the same object; they are compared and averaged to obtain the final reduced spectrum.

In addition to performing the reduction just given, we also modify the reduced spectra in several ways. First we
scale the red spectrum by a multiplicative constant to the same relative flux as the blue spectrum by comparing the region of overlap. Then we correct the spectra for reddening in our galaxy with $E_{B-V}$ values from the maps of Burstein and Heiles (1982). Finally we transform the spectra to the rest frame of the galaxy by using the redshift determined from the upper third of the $[\text{O III}]\lambda 5007$ profile.
Chapter III
CONTAMINATION OF THE PROFILES BY STELLAR ABSORPTION FEATURES

3.1 INTRODUCTION

The observed broad-line profiles of many Seyfert 1 galaxies show considerable structure that is not attributable to the effects of blended emission lines (Weedman 1977; Osterbrock 1978b). Several ideas have been put forth to explain the observed structure:

1. The distribution of gas in the BLR is inhomogeneous. Capriotti, Foltz, and Byard (1981) have constructed discrete-cloud models and they find that the observed structure can be produced by the statistical clumping of $10^3 - 10^4$ clouds in radial velocity space.

2. There are excitation inhomogeneities in the BLR. The combination of a variable continuum source and light travel time effects in the BLR can produce profiles with time-dependent structure (Capriotti, Foltz, and Peterson 1982).

3. The broad emission lines are produced in several distinct kinematic regions. Foltz, Wilkes, and Peterson
(1983) note that there are two large bumps in the Hβ profile of Ark 120 which remain stationary in radial velocity space, but vary in strength over time. They speculate that in addition to the region that produces most of the Hβ emission, there may be additional regions (possibly jets) which produce the two bumps.

4. The intrinsic BLR profiles are contaminated by stellar absorption features from the host galaxy. This possibility has received little attention in the past, but it may be important if the contribution of the host galaxy to the observed Seyfert 1 spectrum is significant.

In this chapter we will evaluate the importance of contamination of the broad-line profiles by stellar absorption features. In particular, we are interested in determining whether stellar contamination can introduce significant structure into the profiles.

3.2 SYNTHETIC PROFILES

We have computed synthetic spectra to investigate the manner in which stellar absorption features affect the broad-line profiles of Seyfert 1 galaxies. The advantage of this approach over a purely observational study is that we can begin with a smooth, symmetric profile, free of any other blended emission lines, and determine how its appearance
and measured properties change with increasing stellar contamination. To illustrate the most important changes that occur in the profiles, we will describe the results for a particular set of components:

1. A featureless power-law spectrum, $F_{\nu} \propto \nu^{-2}$ ($F_{\nu} \propto \lambda$) in particular, represents the nonstellar continuum of a Seyfert 1 galaxy.

2. A spectrum of Gaussian broad emission lines ($H_\alpha$, $H_\beta$, $H_\gamma$, He I $\lambda 5876$) gives the lines that are most studied in the optical. The profiles are characterized by parameters that are fairly typical of Seyfert 1 broad emission lines (Osterbrock 1977, 1978c). The velocity width of each profile is 5000 km s$^{-1}$ (FWHM), the equivalent width of $H\beta$ relative to the continuum is 100 Å, and the fluxes of $H_\alpha$, $H_\gamma$, and He I $\lambda 5876$ relative to $H$ are 5.0, 0.4, and 0.2 respectively.

3. A high signal-to-noise spectrum of the dwarf elliptical galaxy M32 is taken to represent the host galaxy spectrum. There is a certain amount of evidence that Seyfert 1 host galaxies at redshifts $z < 0.02$ are predominately early- or intermediate-type spirals (de Vaucouleurs 1975; Simkin, Su, and Schwarz 1980; Balick and Heckman 1982). If this is the case, then the stellar light from a low-redshift Seyfert should be dominated by a spiral bulge in apertures with project-
ed diameters ≤7". Since dwarf ellipticals and spiral bulges have similar late-type stellar populations (Pritchet 1977; Keel 1983), we will assume in this paper that the M32 spectrum is representative of the host galaxy spectrum of a low-redshift Seyfert.

We will characterize the amount of stellar contamination present in a given spectrum in two different ways:

\[ r(\lambda 4861) = \frac{F_S(\lambda 4861)}{F_n(\lambda 4861)} \] (1)

the ratio of stellar continuum flux to nonstellar continuum flux at 4861 Å, and

\[ \varepsilon(\lambda 4861) = \frac{F_S(\lambda 4861)}{F_S(\lambda 4861) + F_n(\lambda 4861)} \] (2)

the ratio of stellar continuum flux to total continuum flux at 4861 Å. The parameter \( r \) is a convenient one to use in this investigation, whereas \( \varepsilon \), the "stellar fraction", is the parameter normally discussed by observers.

We generated the synthetic spectra by scaling the M32 spectrum and adding it to the sum of the other components. We chose \( \varepsilon(\lambda 4861) = 0.8 \) (\( r=4 \)) as an upper limit to the amount of stellar contamination present, because the largest value of \( \varepsilon(\lambda 4861) \) for our observed Seyferts (presented later) was 0.7 ± 0.1. The synthetic profiles are therefore characterized by values of \( r(\lambda 4861) \) ranging from 0 to 4.
The synthetic profiles in Figure 2 show the structure that is introduced by stellar contamination. We can identify virtually all the absorption features in the profiles with stellar lines observed in late-type stars. The broad Balmer lines are affected at line center by absorption from stellar Balmer lines in the M32 spectrum. Since these central absorption features are not normally seen in observed profiles, we believe that they may be filled in by Balmer emission from the narrow-line regions common to Seyferts. Two extremely strong absorption features are the G band (\(\lambda 4300\)) in the H\textgamma profiles and the Na D doublet (\(\lambda 5893\)) in the He I \(\lambda 5876\) profiles. Most of the other stellar absorption features in the profiles are due to Fe I and Ca I.

Stellar contamination affects not only the appearance of the profiles, but the measurement of their gross properties (e.g., FWHM and flux) as well. We will demonstrate the effects of stellar contamination on the measured properties of H\textbeta, since it the broad emission line most frequently studied. We determined continuum points for the line measurements by selecting a wavelength region on either side of H\textbeta that was reasonably free of observed Seyfert 1 emission lines and strong stellar absorption lines. We then defined the continuum underneath the profile by placing a straight line between the two continuum regions. We kept the same
Figure 2: Synthetic profiles. The profiles are plotted in relative flux units (ergs s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\)) as a function of radial velocity (km s\(^{-1}\)). The stellar and nonstellar continua have been subtracted from each profile. The stellar contamination is specified by \(r(\lambda 4861)\), the ratio of stellar to nonstellar continuum flux at 4861 \(\AA\), and increases from bottom to top in each graph.
two continuum regions for the measurements of the synthetic Hβ profile at each new value of $r(\lambda 4861)$. Since the actual placement of the continuum in an observed Seyfert 1 spectrum is very subjective, our results are only meant to be an example of the types of effects that can occur.

In Figures 3 and 4, we give the measured values of Hβ properties as functions of the stellar contamination. Figure 3a shows that the measured flux, relative to the flux of the broad emission line at zero contamination, decreases linearly with $r(\lambda 4861)$, as might be expected from inspection of Figure 2. However, this effect introduces an error of only $\sim 7\%$ at the largest value of $r(\lambda 4861)$. Figure 3b shows that the measured velocity width (FWHM) of Hβ increases with the stellar contamination, because the peak of the profile is lowered by stellar Hβ absorption. Figure 3c shows a very interesting result: the wavelength of the peak of Hβ shifts to the blue with increasing stellar contamination, due to the presence of Fe I $\lambda 4888$ absorption slightly redward of stellar Hβ absorption. Even at small values of $r(\lambda 4861)$ this effect is important, and could bias studies of the differences in redshift between the broad lines and narrow lines of a Seyfert 1 galaxy. Again, the presence of a narrow Hβ component would diminish this effect, since it would at least partially fill in the central absorption feature due to stellar Hβ.
Figure 3: Measured properties of the synthetic Hβ profiles. The amount of stellar contamination is specified by either $r(\lambda 4861)$ or $c(\lambda 4861)$. (a) The ratio of measured flux to flux at zero contamination. (b) The measured velocity width (FWHM) in km s$^{-1}$. (c) The measured wavelength of the peak of Hβ emission in Å.
Figure 4: Asymmetry of the synthetic Hβ profiles. (a) Asymmetry measured relative to Hβ line peak. (b) Asymmetry measured relative to λ4861.
Figure 4 shows how stellar contamination affects measurements of the asymmetry of Hβ, which we define as

$$A(\lambda_0) = \frac{F_r - F_b}{F_r + F_b}$$

where $F_r$ is the flux of Hβ redward of $\lambda_0$, and $F_b$ is the flux of Hβ blueward of $\lambda_0$. The profile at zero stellar contamination is symmetric by definition, and is therefore characterized by the value $A(\lambda_{4861}) = 0$. As shown in Figure 4, if the asymmetry of the contaminated profile is determined relative to the original line center ($\lambda_0 = 4861$ Å), the Hβ profile is measured to be asymmetric to the blue, because there is more stellar absorption in the red half of the profile. If the asymmetry is determined relative to the line peak, the profile is measured to be rather strongly asymmetric to the red, because the line peak is blueward of 4861 Å.

We have computed synthetic spectra using different values for the Gaussian profile parameters (FWHM, equivalent width of Hβ relative to the nonstellar continuum). We have also generated synthetic spectra with logarithmic profiles, since many observed profiles seem to have logarithmic shapes (Blumenthal and Mathews 1975; Capriotti, Pultz, and Byard 1980). As expected, our results are qualitatively the same as those just described, although the magnitude of
the effects on measured line properties changes. With a better understanding of the effects that stellar contamination might have on a broad-line profile, we can now determine whether these effects are important in observed Seyfert 1 spectra.

3.3 STELLAR FRACTIONS

In order to evaluate the importance of the contamination effects discussed in the previous section, we must know the fraction of light in an observed spectrum that is stellar. This can be done by determining how much a normal galaxy spectrum must be diluted by a nonstellar continuum to give the observed equivalent widths of the stellar absorption features. In Figure 5, the strongest stellar features in the spectrum of M32 are also visible in the spectra of the Seyfert 1 galaxies NGC 4593, NGC 3516, and Mrk 590. With the exception of Mg I b (\(\lambda 5176\)) and Na D (\(\lambda 5893\)), the features labeled are due mostly to Fe I and Ca I (Fay, Stein, and Warren 1974; Pritchet and van den Bergh 1977). We used these features to determine the stellar fraction in an observed Seyfert spectrum because the wavelength region from 5100 \(\AA\) to 6000 \(\AA\) contains strong stellar absorption features and no broad Balmer emission. We did not use the Na D feature, however, because in some of the spectra it could be partially due to interstellar absorption in the host galaxy.
Figure 5: Portions of the spectra of M32 and three Seyfert 1 galaxies. The spectra are scaled to the same flux at \( \lambda 4861 \). The absorption features identified, with the exception of Na D \( \lambda 5893 \), were used to determine \( \epsilon(\lambda 4861) \) in our observed Seyfert spectra.
We did not measure the equivalent widths of the absorption features directly, since the presence of numerous emission lines makes the placement of the continuum extremely difficult. Instead, we scaled the M32 spectrum by a small constant and subtracted it from the Seyfert spectrum, and repeated this procedure until the absorption features disappeared. The values of $\epsilon(\lambda 4861)$ determined in this manner are given in Table 2, and range from $<0.1$ (no stellar features detected) to 0.7. We calculated the redshift ($z$) of each Seyfert in Table 2 from [O III] $\lambda 5007$ and assumed that this was the redshift of the host galaxy.

There are several possible sources of error in $\epsilon(\lambda 4861)$. If the M32 spectrum and the Seyfert spectrum are not aligned in wavelength space or if they are at different resolution, subtraction of the scaled M32 spectrum will result in unusual residual features at the wavelengths of the absorption features. In all cases, however, the errors in wavelength calibrations (determined from dispersion curve fits to comparison lines) are less than 1 Å, and the differences in resolution are less than 1 Å (FWHM) in the middle of the spectra. The effects of these small errors are further minimized by considering the behavior of the entire absorption line when the scaled M32 spectrum is subtracted, and not just the behavior at line center.
<table>
<thead>
<tr>
<th>Seyfert</th>
<th>$Z$</th>
<th>Aperture Diameter</th>
<th>$\epsilon (\lambda 4861)$</th>
<th>$\epsilon (\lambda 5400)$</th>
<th>$10''$ aperture$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 3227</td>
<td>0.004</td>
<td>5''</td>
<td>0.3</td>
<td>0.59</td>
<td></td>
</tr>
<tr>
<td>NGC 3516</td>
<td>0.009</td>
<td>7''</td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 4051</td>
<td>0.002</td>
<td>7''</td>
<td>0.4</td>
<td>0.56</td>
<td></td>
</tr>
<tr>
<td>NGC 4593</td>
<td>0.008</td>
<td>7''</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 5548</td>
<td>0.017</td>
<td>7''</td>
<td>0.3</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>NGC 7469</td>
<td>0.016</td>
<td>5''</td>
<td>0.4</td>
<td>0.48, 0.36$^b$</td>
<td></td>
</tr>
<tr>
<td>Mrk 79</td>
<td>0.022</td>
<td>7''</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mrk 110</td>
<td>0.035</td>
<td>7''</td>
<td>&lt;0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mrk 335</td>
<td>0.026</td>
<td>5''</td>
<td>&lt;0.1</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>Mrk 509</td>
<td>0.034</td>
<td>7''</td>
<td>&lt;0.1</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Mrk 590</td>
<td>0.026</td>
<td>7''</td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3C 120</td>
<td>0.033</td>
<td>7''</td>
<td>&lt;0.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a) Balkan and Filippenko 1983.

b) Results for two different dates.
The dominant source of error is our inability to recognize the exact value of $\epsilon(\lambda 4861)$ at which the absorption features disappear, since the absorption features are superposed on a complicated set of emission lines and blends (especially Fe II). Since a dip between two emission lines can be mistakenly identified as an absorption feature, we compared the residual spectra with those of high-luminosity Seyferts, especially those with strong Fe II (Phillips 1976, 1978), when determining $\epsilon(\lambda 4861)$. We estimate that the uncertainty in $\epsilon(\lambda 4861)$ due to this measurement error is $\pm 0.1$.

Errors in $\epsilon(\lambda 4861)$ may also be introduced if the host galaxy spectrum is substantially different from the spectrum of M32, which has an integrated spectral type of G3 (Humason, Mayall, and Sandage 1956). An obvious extreme example is the host galaxy of 3C 48, which has an integrated spectral type of about A7, and is exceedingly luminous (Boroson and Oke 1982). Malkan and Filippenko (1983) and Goodrich and Osterbrock (1983) demonstrate that significant errors in the determination of the stellar fraction of a Seyfert spectrum can result from an incorrect choice of a normal galaxy. However, we believe that to first order the M32 spectrum is a good choice for the normal galaxy spectrum, since all the strong stellar features can be made to vanish from the Seyfert spectra. More accurate determina-
tion of the host galaxy spectrum is clearly the next level of sophistication and should be attempted in the future.

It should also be noted that inaccurate subtraction of the host galaxy spectrum may result if the velocity dispersion of the host galaxy differs substantially from the velocity dispersion of M32. However, differences in velocity dispersions, if less than 300 km s\(^{-1}\), lead to errors smaller than those discussed for resolution differences.

The contribution of the stellar flux to the total flux in a given aperture has been measured for a large number of Seyfert 2 galaxies (Koski 1978; Shuder 1981) and Seyfert 1.8 and 1.9 galaxies (Osterbrock 1981; Goodrich and Osterbrock 1983). Fewer measurements have been made for Seyfert 1 galaxies, because of the difficulties introduced by the presence of strong broad emission lines. The stellar fractions measured by Osterbrock (1978c) from the Ca II K absorption line cannot be compared to ours, because the host galaxy contributes much less to the continuum flux at the wavelength of Ca II K (3934 Å) than it does at 4861 Å.

Recently, Malkan and Filippenko (1983) determined stellar and nonstellar fluxes of nine Seyfert 1 galaxies from high resolution (1.6 Å) spectra and direct images. The stellar fractions that we calculated from these fluxes for each of the six galaxies that we have in common are given in the last column of Table 2. Considering the variable
nature of these objects and the fact that our observations were made one to three years later, our values are remarkably consistent with theirs. In fact, our value is approximately equal to or slightly smaller than theirs for each galaxy, which is to be expected since their measurements are at a slightly longer wavelength (5400 Å) and are quoted for 10" apertures. We also agree with Malkan and Filippenko that most of the Na D absorption in the spectrum of NGC 3227 is due to interstellar gas associated with that galaxy, since the absorption is still extremely strong in our spectrum after it has been corrected for stellar contamination.

3.8 REMOVAL OF THE STELLAR CONTAMINATION

Can subtraction of the scaled M32 spectrum successfully remove stellar absorption features from the observed broad-line profiles? We can answer this question by considering spectra of the Seyferts with the greatest amount of stellar contamination. Figures 6-8 give the observed and corrected spectra of these Seyferts. A scan of Mrk 335, a Seyfert with no detectable stellar absorption features, is shown in Figure 9 for comparison purposes. It is interesting to note that the corrected spectra are very similar in appearance to the spectra of Mrk 335 and other high-luminosity Seyfert 1 galaxies; in particular they all have nearly flat
continua. This gives us additional confidence that our values of $c(\lambda 4861)$ are approximately correct.

Although the structure in the $H\beta (\lambda 4861)$ and $H\gamma (\lambda 4340)$ profiles does not disappear completely, the corrected profiles are certainly smoother and more symmetric than the observed profiles. The He I $\lambda 5876$ profiles, which are affected by strong molecular TiO as well as Na D absorption, are not corrected well enough to be very useful. We could not detect any stellar absorption features in our Hα profiles, which is to be expected since Hα is by far the strongest emission line in the optical.
Figure 6: IDS scan of NGC 3516: observed (upper) and corrected for stellar contamination (lower). The spectra are plotted in relative flux units (ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$) as a function of wavelength (Å).
Figure 7: IDS scan of NGC 4593: observed (upper) and corrected for stellar contamination (lower). The spectra are plotted as in Figure 6.
Figure 8: IDS scan of Mrk 590: observed (upper) and corrected for stellar contamination (lower). The spectra are plotted as in Figure 6.
Figure 9: IDS scan of Mrk 335 (observed). No stellar features were detected in this scan. The spectrum is plotted as in Figure 6.
3.5 Discussion

Osterbrock and Shuder (1982) have shown that the broad emission line profiles of Seyfert 1 galaxies should be corrected for contamination by other broad and narrow emission lines. We have demonstrated that some profiles must also be corrected for stellar absorption contamination, which introduces structure into the observed profiles. We find that we can remove most of the small-scale features in our Hβ and Hγ profiles by subtracting a suitably scaled M32 spectrum.

The effects of stellar contamination can be reduced by using apertures that are smaller than the ones we have used. Smaller apertures will reduce the structure in the broad-line profiles, but they may also introduce errors in line measurements caused by atmospheric seeing (Peterson and Collins 1983), guiding errors, and atmospheric refraction. Also, reducing the projected aperture area by a certain factor will not reduce the stellar flux by the same fraction, because the aperture is still centered on the brightest part of the host galaxy.

The stellar contamination of a Seyfert 1 spectrum would increase, of course, if the Seyfert were placed at a higher redshift, because more of the host galaxy would be included in the aperture. However, the opposite effect is seen in Table 2: there is a general trend toward smaller stellar
fractions at large redshifts. The reason for this is that we observed Seyferts that are apparently very bright, and therefore have not included low-luminosity Seyferts at high redshifts.

Finally, we note that stellar contamination can affect the results of spectral variability studies, because the changing nonstellar continuum results in different degrees of stellar contamination at different times. If the observed continuum is assumed to entirely nonstellar, when in reality there is a large stellar contribution, then fractional changes in the nonstellar continuum are seriously underestimated. Fractional changes in the Hβ flux are only slightly in error, however, because the effects of stellar contamination on the measurement of the Hβ flux are small. Another interesting effect is that structure in an Hβ profile due to stellar features is enhanced (relative to the rest of the profile) when the Hβ flux is small and diminished when the Hβ flux is large. An observer unaware of this effect would assume that the change in structure that accompanies a change in flux represents a real change in the emission line profile.
Chapter IV

CONTAMINATION OF THE PROFILES BY EMISSION FEATURES

4.1 INTRODUCTION

The study of the optical spectra of Seyfert 1 galaxies is made difficult by the fact that the broad lines of interest are often blended with other broad and narrow emission lines. The narrow-line contamination is easily identified and can be removed successfully from the broad-line profiles in most cases (Osterbrock and Shuder 1982; Cohen 1983), but the broad-line contamination is more difficult to identify and remove. An extended shelf of emission seen in the red wing of many Hβ profiles is probably broad-line contamination, since it is not seen in the profiles of Hα or Hγ. Osterbrock and Shuder (1982) attribute the shelf to Fe II λλ4924, 5018 emission, which is in the same wavelength region as the shelf and can be identified in Seyfert 1 galaxies with relatively narrow permitted lines (Phillips 1976, 1977, 1978). De Robertis (1985) gives a procedure to remove the shelf from the Hβ profile which assumes that the shelf is entirely Fe II emission.
Recent evidence indicates that emission from a species other than Fe II contributes to the shelf. Meyers and Peterson (1985) find that the strength of the shelf is only very weakly correlated with the strength of the Fe II blends near 4570 Å and 5250 Å. They also find that a strong shelf is often present even when Fe II emission is extremely weak. These results are confirmed by van Groningen (1984), who finds that the removal of Fe II $\lambda\lambda$4924, 5018 in an amount consistent with the strength of Fe II $\lambda$5169 (which is to the red of the shelf) leaves strong residual emission in most cases.

The possibility that broad [O III] $\lambda\lambda$4959, 5007 emission exists has been discussed in the past (Osterbrock 1978b; Shields 1978), and it seems that broad [O III] is a good candidate for the excess shelf emission. The identification of broad [O III] would be extremely useful for two reasons: (1) it would allow better removal of the shelf that contaminates the H profile and (2) it would provide an estimate of the densities in the broad-line region (BLR).

The evidence that there is another species contributing to the shelf of emission is based on the observed strength of the shelf; proof that this species is broad [O III] emission however must come from the observed shape of the shelf. One way to investigate the shape of the shelf is to
assume that the intrinsic Hβ profile is known. Meyers and Peterson (1985) use this method for the Seyfert I galaxy Akn 120 by folding the blue, unblended half of the Hβ profile about various wavelengths until it approximately matches the red half between 30% and 70% of the strength at the peak of the line. They then subtract the folded symmetric profile from the Hβ/shelf blend, and use the symmetric profile as a template to model the shelf of emission in Akn 120. They find that a combination of broad [O III] and Fe II emission is a much better match to the observed shelf than Fe II emission alone. Foltz, Wilkes, and Peterson (1983) reach the same conclusion for Akn 120 by using the Hγ profile as a template.

We will use another method to study the shelf which is based on the methods that Osterbrock and Shuder (1982) and De Robertis (1985) use to remove Fe II. This method assumes that the profiles of the contributors to the shelf are known, and that subtraction of these contributors in the correct amount will result in a fairly smooth Hβ profile. For this investigation we prefer this method, because we are interested in studying the asymmetries of the profiles and the differences among them and therefore cannot assume that the Hβ profile is symmetric or given by another profile.
4.2 CONTINUUM RANGES

We identified the continuum ranges for a Seyfert 1 galaxy by combining its blue and red spectra and fitting all of the regions that appeared to be relatively free of emission lines with a 2nd degree polynomial. The regions that yielded the best fit from 4000 Å to 7000 Å were selected as continuum ranges. The centers of the continuum ranges chosen are near the wavelengths 4200 Å, 5100 Å, 5650 Å, 6200 Å, and 6850 Å, and the ranges are normally 30 - 40 Å wide.

We resampled our spectra to a bin size of half a resolution element (~4.5 Å) for the purpose of estimating the signal-to-noise of the continuum. We determined a lower limit to the signal-to-noise from the variance of a linear fit to an individual continuum region. The signal-to-noise may be higher than the value determined because weak unidentified emission lines may be present in the continuum regions. The signal-to-noise of the continuum in a resampled spectrum must be greater than or equal to 70 to be included in our profile analysis.

Three Seyfert 1 galaxies are excluded from further analysis in this investigation. The continuum of Mrk 590 does not satisfy the signal-to-noise requirements, and we suspect that much of the "noise" results from incomplete subtraction of the host galaxy spectrum (Chapter III).
NGC 3227 is excluded as a result of the difficulties encountered in removing the narrow-line contamination: the narrow-line profiles of different species are very dissimilar and deserve further study at higher resolution. Finally, NGC 4051 is excluded because its broad-line profiles are very narrow relative to those of the other Seyferts considered here, and are seriously altered by convolution with the instrumental profile.

4.3 REMOVAL OF THE NARROW LINES

The technique for deblending narrow emission lines from the broad-line profiles involves using the narrow [O III] $\lambda 5007$ line as a template, reproducing it at another wavelength, and scaling it by a constant in strength and width. The template is scaled and subtracted from the overall blend by trial-and-error until the subtraction leaves a smooth broad-line profile. The template must be scaled in width because the velocity resolution is better at longer wavelengths. For example, the [O III] $\lambda 5007$ template is always scaled in width by a factor less than one to match the narrow-lines that contaminate the broad $H\alpha$ profile. This method is inherently imperfect, because an observed profile is a convolution of the intrinsic profile (which is not Gaussian) and the instrumental profile (which is Gaussian to a good approximation). The contribution of the instru-
mental profile to the width of the observed profile decreases with wavelength; thus profiles at different wavelengths cannot be matched exactly by simply scaling their widths. This procedure still works rather well however at this resolution.

The following iterative procedure removes the emission-line contamination from the broad-line profiles of interest:

1. Using the narrow [O III] $\lambda 5007$ profile as a template, remove the narrow lines blended with the broad H$\alpha$ profile.

2. Using the decontaminated H$\alpha$ profile as a template, remove the shelf of emission in the red wing of the H$\beta$ profile (discussed in detail in the next section).

3. Remove [O III] $\lambda 4959$ with the [O III] $\lambda 5007$ template to recover the blue wing of the intrinsic [O III] $\lambda 5007$ profile. The scale factor in this case is known from the ratio of the transition probabilities of the two lines.

4. Repeat the above procedure with the improved [O III] $\lambda 5007$ template.

In practice, only two passes through the procedure are needed. It is then possible to use the improved [O III] $\lambda 5007$ and broad H$\alpha$ templates to remove emission-line contamination from other broad-line profiles.
Table 3 gives the relative narrow-line intensities derived from the deblending process. The intensities of [O III] $\lambda$4959, [O I] $\lambda$6364, and [N II] $\lambda$6548 can be determined easily from the ratio of their transition probabilities to those of [O III] $\lambda$5007, [O I] $\lambda$6300, and [N II] $\lambda$6584 respectively (Osterbrock 1974). The major source of error in the intensity of a line is our inability to recognize the exact value that results in the "smoothest" broad-line profile after subtraction of the line. We estimate that the internal percentage error is $\sim$10% for the lines of [N II] and [S II] and $\sim$20% for the weaker lines of [O III] ($\lambda$4363) and [O I]. The narrow Balmer lines are more difficult to remove from their broad-line counterparts, and their intensities are likely to have internal percentage errors of at least 20%. Comparison of our measurements with those of Osterbrock (1982) and Cohen (1983) for the galaxies we have in common indicates percentage differences of less than 20 - 25% in the intensities.

The narrow Hα/Hβ ratio is always greater than the case B recombination value of $\sim$2.8, which is to be expected since recent photoionization calculations indicate that this value should be greater than 2.8 in the narrow-line region (Ferland and Osterbrock 1985). Also, reddening by dust in the narrow-line region would result in an even higher Hα/Hβ value. This gives us confidence that our removal of the
narrow components of the Balmer lines is at least approximately correct. The broad lines with widths (FWHM) less than 3000 km s\(^{-1}\) are likely to have weak narrow components that are undetectable at this resolution.
Table 3

Narrow-Line Intensities ([O III] λ5007 = 1.0)

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 3516</td>
<td>0.03</td>
<td>0.06</td>
<td>0.09</td>
<td>0.23</td>
<td>0.30</td>
<td>0.13</td>
<td>0.12</td>
</tr>
<tr>
<td>NGC 4593</td>
<td>0.07</td>
<td>0.06</td>
<td>0.09</td>
<td>0.50</td>
<td>0.48</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>NGC 5548</td>
<td>0.08</td>
<td>0.13</td>
<td>0.05</td>
<td>0.60</td>
<td>0.21</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>NGC 7469</td>
<td>0.01&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.31</td>
<td>0.09</td>
<td>1.30</td>
<td>0.60</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>Mrk 79</td>
<td>0.01&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.08</td>
<td>0.06</td>
<td>0.28</td>
<td>0.30</td>
<td>0.14</td>
<td>0.10</td>
</tr>
<tr>
<td>Mrk 110</td>
<td>0.09</td>
<td>----</td>
<td>0.08</td>
<td>----</td>
<td>0.09</td>
<td>0.10</td>
<td>0.09</td>
</tr>
<tr>
<td>Mrk 335</td>
<td>0.01&lt;sup&gt;a&lt;/sup&gt;</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>0.09</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>Mrk 509</td>
<td>0.02&lt;sup&gt;a&lt;/sup&gt;</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>0.15</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>3C 120</td>
<td>0.02&lt;sup&gt;a&lt;/sup&gt;</td>
<td>----</td>
<td>0.03</td>
<td>----</td>
<td>0.12</td>
<td>0.04</td>
<td>0.03</td>
</tr>
</tbody>
</table>

<sup>a</sup> Relative uncertainties are ~50%.
4.4 REMOVAL OF THE SHELF OF EMISSION FROM Hβ

To investigate the shape of the shelf of emission in the red wing of Hβ we consider two cases. In the first case, we assume that the shelf is entirely Fe II λλ4924, 5018 emission. In the second case, we assume that the flux of Fe II λλ4924, 5018 is known from the Fe II blend at 5250 Å, and the rest of the shelf is broad [O III] λλ4959, 5007 in the expected 1:3 ratio. In both cases we use the decontaminated Hα profile as a template, since the Fe II profiles are similar to the Balmer profiles in Seyfert 1 galaxies with relatively narrow permitted lines (Phillips 1977, 1978). We also take the ratio of Fe II λ4924 to Fe II 5018 to be 1.0, because Phillips (1978) finds that the intensities of the two lines are approximately equal in two Seyfert 1 galaxies where the lines could be isolated. Also, theoretical considerations indicate that the ratio of these two lines is unity to within 15% in BLR clouds (van Groningen 1984). The procedure that we follow in both cases is to subtract as much of the shelf as possible without allowing the residual Hβ profile to drop below the adopted continuum level.

We give the results for the first case in Figures 10 and 11 for Mrk 509 and Mrk 110 respectively. These figures show the original spectrum around Hβ, the profiles of the Fe II lines subtracted, and the residual Hβ profile.
sharp dip at ~4924 Å in the residual profiles of both Seyferts is strong evidence that Fe II is not the only contributor to the shelf. In other words, the removal of Fe II λ5018 in an amount sufficient to eliminate the red end of the shelf results in too much subtraction of Fe II λ4924.

In the second case, we assume that the ratio of Fe II λ4924, 5018 to the Fe II blend at 5250 Å is 0.19, since Phillips (1978) finds this intensity ratio is 0.19 ± 0.03 for four Seyfert 1 galaxies with relatively narrow permitted lines. We believe that this assumption is valid for Seyferts with broader permitted lines, because the relative intensities of individual Fe II lines are apparently very similar among all Seyferts (Phillips 1978). We assume that the rest of the shelf is broad [O III] emission with the same profiles as Hα. In Figures 12 and 13 we give the original Hβ profile, the combined profiles of the Fe II and broad [O III] lines subtracted, and the residual Hβ profile for Mrk 509 and Mrk 110. The residual Hβ profile in this case is smooth, suggesting that the assumption that broad [O III] contributes to the shelf in these two Seyferts may indeed be valid.

To discuss the results for our entire collection of Seyferts, we must divide them into two groups. For Seyfert 1 galaxies whose Hβ widths (FWHM) are less than or approxi-
Figure 10: Mrk 509 deblend assuming shelf is entirely Fe II. The original spectrum, the residual Hβ profile, and the Fe II profiles that were subtracted are given.
Figure 11: Mrk 110 deblend assuming shelf is entirely Fe II. The original spectrum, the residual Hβ profile, and the Fe II profiles that were subtracted are given.
Figure 12: Mrk 509 deblend assuming shelf is Fe II and broad [O III]. The original spectrum, the residual Hβ profile, and the Fe II and broad [O III] profiles that were subtracted are given.
Figure 13: Mrk 110 deblend assuming shelf is Fe II and broad [O III]. The original spectrum, the residual Hβ profile, and the Fe II and broad [O III] profiles that were subtracted are given.
mately equal to 3000 \( \text{km s}^{-1} \) (Mrk 110, Mrk 335, Mrk 509, and 3C 120), the assumption that the shelf is entirely Fe II results in a residual H\( \beta \) profile with a sharp artificial dip at 4924 Å, whereas the assumption that the Fe II emission is known and the rest of the shelf is broad [O III] results in a smoother profile. For Seyfert 1 galaxies whose H\( \beta \) widths (FWHM) are greater than 3000 \( \text{km s}^{-1} \) (NGC 3516, NGC 4593, NGC 5548, NGC 7469, and Mrk 79), the two cases are virtually indistinguishable: both assumptions result in rather smooth profiles because the lines are so broad that the shape of the shelf is rather insensitive to the exact central wavelength of the contributors.

Table 4 gives a summary of our results for the case where broad [O III] contributes to the shelf of emission. It is evident from a comparison of the first two columns that broad [O III] can contribute several times the flux that Fe II contributes to the shelf in some cases. We must note however that this is not a complete representative sample of Seyfert 1 galaxies, since Seyferts with extremely strong Fe II were not observed.

We can estimate the average electron number density in the BLR clouds using the same argument given by Meyers and Peterson (1985). In the narrow-line region, the [O III] \( \lambda\lambda 4959,5007/\text{H}\beta \) ratio is approximately 16 and the density is less than \( 10^5 \) (Koski 1978), the critical den-
ity for collisional deexcitation of the [O III] lines. Assuming that the [O III] emission is suppressed relative to a low-density value of 16 by collisional deexcitation, the density can be calculated. The [O III]/Hβ ratio, averaged over all of the Seyferts in Table 4, is 0.10 ± 0.03, which corresponds to a density of ~10⁶ cm⁻³. This value is only a rough estimate, since a proper determination of the dependence of the [O III]/Hβ ratio on the physical conditions in the BLR must await detailed photoionization calculations.
Table 4
Properties of the Extended Shelf of Emission

<table>
<thead>
<tr>
<th>Seyfert Galaxy</th>
<th>Fe II&lt;sup&gt;a&lt;/sup&gt;</th>
<th>[O III]&lt;sup&gt;b&lt;/sup&gt;</th>
<th>[O III]&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 3516</td>
<td>0.010</td>
<td>0.028</td>
<td>0.102</td>
</tr>
<tr>
<td>NGC 4593</td>
<td>0.047</td>
<td>0.012</td>
<td>0.033</td>
</tr>
<tr>
<td>NGC 5548</td>
<td>0.008</td>
<td>0.020</td>
<td>0.124</td>
</tr>
<tr>
<td>NGC 7469</td>
<td>0.029</td>
<td>0.020</td>
<td>0.086</td>
</tr>
<tr>
<td>Mrk 79</td>
<td>0.011</td>
<td>0.024</td>
<td>0.089</td>
</tr>
<tr>
<td>Mrk 110</td>
<td>0.007</td>
<td>0.024</td>
<td>0.108</td>
</tr>
<tr>
<td>Mrk 335</td>
<td>0.015</td>
<td>0.028</td>
<td>0.112</td>
</tr>
<tr>
<td>Mrk 509</td>
<td>0.006</td>
<td>0.032</td>
<td>0.124</td>
</tr>
<tr>
<td>3C 120</td>
<td>0.011</td>
<td>0.024</td>
<td>0.101</td>
</tr>
</tbody>
</table>

a) Fe II λλ4924, 5018

b) [O III] λλ4959, 5007
9.5 DISCUSSION

The evidence that Fe II is not the only species that contributes to the shelf of emission has been largely based on the observed strength of the shelf. We have shown that the shape of the shelf is also inconsistent with the idea that Fe II emission alone is responsible for the shelf. If we relax the assumption that the intensities of Fe II λ4924 and Fe II λ5018 are equal, we find that we can obtain a smooth residual Hβ profile only if this ratio varies from 1 to 5 among the Seyferts in our collection. However, as discussed in the last section, there is both observational and theoretical evidence that the ratio of these two lines is always close to unity.

The assumption that broad [O III] contributes to the shelf leads to a smooth, but not perfect Hβ profile. In particular, a broad residual emission feature is often seen in the neighborhood of 5050 Å after subtraction of the shelf (Figures 12 and 13). There are three possible reasons for this excess emission:

1. Broad [O III] is not a significant contributor to the shelf.
2. The [O III] profile has much stronger wings than the Hα template.
3. There is weak broad emission in this range from yet another species. Van Groningen (1984) gives evidence
that Si II $\lambda\lambda 5041,5056$ emission may contribute up to 20% of the shelf, based on the observed intensity of Si II lines in the ultraviolet.

We prefer the last possibility given above since the central wavelength of the residual emission is near 5050 Å. Peterson et al. (1985) note that there is indeed a distinct feature present at 5050 Å in spectra of Akn 120. Throughout the rest of this investigation we will assume that broad [O III] is present, and that we can remove the [O III] and Fe II contamination well enough to study the intrinsic Hβ profile.

Finally, we note that the density derived from the broad [O III]/Hβ ratio ($\sim 10^8$ cm$^{-3}$) is at the low end of those used for BLR photionization models ($10^6$ - $10^{10}$ cm$^{-3}$). Furthermore, Peterson et al. (1985) suggest that the density of the Hβ-emitting region in Akn 120 is $10^{10}$ - $10^{11}$ cm$^{-3}$. It is likely that there is a wide range of densities in the BLR and that $10^8$ cm$^{-3}$ represent some sort of average. If this is the case, then the clouds emitting the majority of the broad [O III] flux may be of even lower density than that quoted. Therefore an attempt should be made in the future to extend the present photoionization calculations to both lower and higher densities.
Chapter V
THE DECONTAMINATED PROFILES AND PROFILE RATIOS

5.1 RESOLUTION CORRECTIONS

We will study the broad emission line profiles of Hβ, Hα, and He I λ5876 in this chapter, since these are the only profiles suitable for further analysis. Attempts to decontaminate the Hγ and He II λ4686 profiles reveal that they are too severely contaminated by Fe II emission to be useful in most cases. The He I λ5876 profile will only be considered for those Seyferts characterized by stellar fractions less than or equal to 0.1, since stellar contamination severely alters this profile and cannot be removed satisfactorily (Chapter III).

The resolution near the center of our spectra is ~9 Å (FWHM), which corresponds to a velocity resolution of 411 km s⁻¹ at the position of Hα and 555 km s⁻¹ at the position of Hβ. The narrowest permitted lines in our collection have widths of 1500 km s⁻¹ (FWHM); convolution with the instrumental profile may have a significant effect on their observed profiles. In order to compare the profiles of lines at different wavelengths therefore the profiles should all be corrected to the same velocity resolution.
We begin this process by first subtracting the continuum underneath a decontaminated profile using the continuum regions given in Chapter IV. We then convert the profiles to units of relative flux per unit radial velocity interval to facilitate the comparison of profiles at different wavelengths. Since the instrumental profile is Gaussian to a good approximation (Chapter II), a profile can be degraded to lower resolution by simply convolving it with a Gaussian profile of the appropriate width. The resolution of the Hα profile is therefore degraded to the resolution of the Hβ profile by convolution with a Gaussian of width 373 km s⁻¹. He I λ5876 is much closer to the end of the spectral scan than Hα or Hβ, so its resolution is ~11 Å instead of ~9 Å (Chapter II). This corresponds to a velocity resolution of 562 km s⁻¹, which is very close to the velocity resolution of Hβ, and therefore no resolution correction is needed.

5.2 ANALYSIS OF THE PROFILES
In Appendix A, we give the profiles corrected for stellar contamination, emission-line contamination, and different velocity resolutions. For comparison with the profiles of Osterbrock and Shuder (1982), we also give profiles corrected for stellar contamination and different velocity resolutions, but not for emission-line contamination. No attempt has been made to remove He II λ4686 from the Hβ
profile or [Fe VII] $\lambda 5721$, 6087 and [N II] $\lambda 5755$ from the He I $\lambda 5876$ profile. These contaminants are too far from line center to have an effect on the analysis that follows.

The profiles are given in units of relative flux per unit velocity interval, the peak of the broad component is normalized to a value of 10, and the continuum level is at zero. Furthermore, we assume that the broad lines are at the same redshift as the narrow [O III] $\lambda 5007$ line. The measured position of the peak of the broad-line profiles is always within 200 km s$^{-1}$ of zero velocity, and the average displacement of both the Hα and Hβ peak is 90 km s$^{-1}$ to the red of zero velocity. The offset of the peak from zero velocity is always small compared to the width of the line in all cases, so choosing the position of the peak to represent zero velocity would not change any of our measurements significantly.

Our profiles can be compared with those of others taken at earlier epochs for the galaxies we have in common. De Robertis (1985) gives Hβ profiles for NGC 3516, NGC 5548, NGC 7469, Mrk 79, Mrk 335, and Mrk 509. Osterbrock and Shuder (1982) give Hα, Hβ, and He I $\lambda 5876$ profiles for Mrk 79 and Mrk 335. A comparison of our profiles with those from these earlier studies indicates that no drastic changes have occurred in any of the profiles.
Table 5 presents the intensities of the broad emission lines relative to the narrow [O III] $\lambda$5007 flux. The relative intensity of H$\gamma$ has not been corrected for Fe II contamination, but the other lines have been corrected for all of the contamination effects discussed in the previous chapters. The major source of uncertainty in the intensities is the placement of the continuum, and we estimate that the relative percentage error in a line intensity is 10 - 15%.

The full widths at half maximum (FWHM) of H$\alpha$ and H$\beta$, in units of km s$^{-1}$, are given in Table 6. The H$\beta$ profile is broader than the H$\alpha$ profile in every Seyfert 1 galaxy; the reason for this difference will be discussed in detail in the next section. Table 6 also gives the asymmetry of the H$\alpha$ and H$\beta$ profiles, which we define as

$$\text{Asym} = \frac{\text{FWHM}(R) - \text{FWHM}(B)}{\text{FWHM}(R) + \text{FWHM}(B)}$$  \hspace{1cm} (4)$$

where FWHM(R) and FWHM(B) are the half widths at half maximum redward and blueward of line center respectively.

We can estimate the errors in the asymmetries by choosing different continuum placements and by measuring the east and west data separately. We find that the errors in the asymmetries are less than 0.1 in all cases, and that the asymmetry of H$\alpha$ is the same as the asymmetry of H$\beta$. to
Table 5

Broad-Line Intensities \([\text{O III}] \lambda 5007 = 1.0\)

<table>
<thead>
<tr>
<th>Seyfert Galaxy</th>
<th>H\text{y} (\lambda 4340)</th>
<th>H\text{b} (\lambda 4861)</th>
<th>He I (\lambda 5876)</th>
<th>Ha (\lambda 6563)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 3516</td>
<td>1.16</td>
<td>2.63</td>
<td>0.41</td>
<td>9.60</td>
</tr>
<tr>
<td>NGC 4593</td>
<td>2.06</td>
<td>2.87</td>
<td>0.82</td>
<td>7.91</td>
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<tr>
<td>NGC 5548</td>
<td>0.84</td>
<td>1.86</td>
<td>0.31</td>
<td>11.55</td>
</tr>
<tr>
<td>NGC 7469</td>
<td>0.85</td>
<td>1.32</td>
<td>0.21</td>
<td>5.67</td>
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<tr>
<td>Mrk 79</td>
<td>1.30</td>
<td>2.34</td>
<td>0.79</td>
<td>3.70</td>
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<tr>
<td>Mrk 110</td>
<td>0.74</td>
<td>1.71</td>
<td>0.29</td>
<td>7.70</td>
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<tr>
<td>Mrk 335</td>
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<td>3.93</td>
<td>0.73</td>
<td>15.72</td>
</tr>
<tr>
<td>Mrk 509</td>
<td>1.04</td>
<td>2.49</td>
<td>0.71</td>
<td>9.61</td>
</tr>
<tr>
<td>3C 120</td>
<td>0.54</td>
<td>1.25</td>
<td>0.40</td>
<td>5.25</td>
</tr>
</tbody>
</table>
within the errors of measurement. If we conservatively
designate all profiles with values $> 0.1$ as being asymme-
tric, then five Seyferts have symmetric profiles, two Sey-
ferts have profiles that are asymmetric to the blue, and
two Seyferts have profiles that are asymmetric to the red.
We are in agreement with Osterbrock and Shuder (1982) and
De Robertis (1985), who find that most broad-line profiles
are symmetric, and that there is roughly an equal number of
blue and red asymmetries.
Table 6

_Broad-Line Widths and Asymmetries_

<table>
<thead>
<tr>
<th>Seyfert Galaxy</th>
<th>PWHM (Hβ)</th>
<th>PWHM (Hα)</th>
<th>Asym (Hβ)</th>
<th>Asym (Hα)</th>
</tr>
</thead>
<tbody>
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<td>NGC 3516</td>
<td>4760</td>
<td>3650</td>
<td>-0.14</td>
<td>-0.23</td>
</tr>
<tr>
<td>NGC 4593</td>
<td>4900</td>
<td>3720</td>
<td>+0.07</td>
<td>-0.01</td>
</tr>
<tr>
<td>NGC 5548</td>
<td>4940</td>
<td>5010</td>
<td>-0.01</td>
<td>-0.03</td>
</tr>
<tr>
<td>NGC 7469</td>
<td>3460</td>
<td>2450</td>
<td>+0.29</td>
<td>+0.24</td>
</tr>
<tr>
<td>Mrk 79</td>
<td>5140</td>
<td>4000</td>
<td>-0.06</td>
<td>-0.08</td>
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<tr>
<td>Mrk 110</td>
<td>1970</td>
<td>1820</td>
<td>+0.28</td>
<td>+0.24</td>
</tr>
<tr>
<td>Mrk 335</td>
<td>1720</td>
<td>1490</td>
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<tr>
<td>Mrk 509</td>
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<td>2570</td>
<td>-0.09</td>
<td>-0.05</td>
</tr>
<tr>
<td>3C 120</td>
<td>2070</td>
<td>2010</td>
<td>-0.02</td>
<td>+0.01</td>
</tr>
</tbody>
</table>
5.3 Analysis of the Profile Ratios

An efficient way to investigate the variation of physical conditions across the BLR is to analyze the "profile ratios". A profile ratio is formed by dividing one profile by another, point by point. We present the profile ratios of Hβ/Hα and He I λ5876/Hβ for individual Seyfert 1 galaxies in Appendix B. The ratios are terminated at radial velocities of -4000 and +4000 km s\(^{-1}\) for the reasons given later in this section. For eight out of a total of nine Seyferts, the Hβ/Hα ratio increases by a factor of \(\sim 2\) from 0 to \(\pm 4000\) km s\(^{-1}\); the Hβ/Hα ratio for NGC 5548 shows only a marginal increase. In other words, the Hβ profile has a greater FWHM than Hα, as demonstrated in Table 6. The He I/Hβ ratio given for five Seyferts, although noisier than the Hβ/Hα ratio, also increases with the absolute value of the radial velocity.

Our results confirm the discovery by Shuder (1982, 1984) that the Hβ/Hα and He I/Hβ ratios increase with radial velocity in most of the Seyfert 1 galaxies he studied. As pointed out by Shuder (1982), reddening by dust in the intercloud medium cannot account for the variation in the line ratios with radial velocity. In this case one would infer that the reddening decreases with radial velocity from the Hβ/Hα ratio, but that the reddening increases with radial velocity from the He I/Hβ ratio, which is a contradiction.
Although correction for contamination effects does not alter the fact that the \(\text{H}\beta/\text{H}\alpha\) and \(\text{He}\ I/\text{H}\beta\) ratios increase with radial velocity, it does allow for a more accurate determination of the intrinsic ratios. We will demonstrate that contamination effects can significantly change the profile ratios by considering the cases in which these effects make the largest contribution. Figures 14-16 present the corrected ratios as histogram plots, and the ratios for which one specific correction is not made as smooth plots. In all cases, the contamination effects tend to either lower the ratio in the core or raise the ratio in the wings, as discussed in Chapter I.

Figure 14 gives the \(\text{H}\beta/\text{H}\alpha\) ratio for MGC 3516, the Seyfert with the greatest stellar fraction at 4861 Å (=0.7). The stellar contamination lowers the ratio in the core by \(\sim 15\%\) and has little overall effect on the ratio in the wings. In Figure 15, we see the effects of the shelf of emission in the red wing of \(\text{H}\beta\) on the \(\text{H}\beta/\text{H}\alpha\) ratio of Mrk 509, which has the strongest shelf relative to \(\text{H}\beta\). The shelf of emission begins to have an effect at 2000 \(\text{km s}^{-1}\), and raises the ratio by \(\sim 20\%\) at 4000 \(\text{km s}^{-1}\). Redward of 4000 \(\text{km s}^{-1}\), the effects of the shelf on the \(\text{H}\beta/\text{H}\alpha\) ratio become very strong, and the errors involved in the removal of the shelf become very large. In Figure 16 we see that dividing the \(\text{H}\alpha\) profile at its original resolution by the
Figure 14: Hβ/Hα profile ratio for NGC 3516. The histogram plot is the corrected ratio and the smooth plot is the ratio that has not been corrected for stellar contamination.
Figure 15: Hβ/Hα profile ratio for Mrk 509. The histogram plot is the corrected ratio and the smooth plot is the ratio that has not been corrected for the presence of the shelf of emission in the red wing of Hβ.
Figure 16: $\text{H}_\beta/\text{H}_\alpha$ profile ratio for Mrk 335. The histogram plot is the corrected ratio and the smooth plot is the ratio that has not been corrected for velocity resolution differences.
Hβ profile results in a Hβ/Hα ratio that is lower in the core by \( \sim 10\% \) compared to the corrected Hβ/Hα ratio.

We find that each of the three effects we have considered can alter the observed Hβ/Hα profile ratios significantly. The combination of these effects systematically lead to a larger apparent increase in Hβ/Hα from the core to the wings. Finally, we note that to accurately compare theoretical profile ratios from models with the observed ratios here, the theoretical profiles must be convolved with an instrumental profile of appropriate width.

We terminate the profile ratios at -4000 and +4000 km s\(^{-1}\) for several reasons. For the Seyferts with relatively narrow permitted lines, the profiles begin to approach the continuum between 4000 and 6000 km s\(^{-1}\), and the profile ratios become very noisy. For the Seyferts with relatively broad permitted lines, the He II \( \lambda 4686 \) profile, which cannot be removed, contributes significantly to the emission in the blue wing of the Hβ profile at about -5000 km s\(^{-1}\) (relative to Hβ line center). Also, the intrinsic Hβ profile begins to drop below the shelf contribution between +4000 and +6000 km s\(^{-1}\). If the strength of the shelf is in error by 20%, then the Hβ intensity is in error by 20% at the point where it equals the shelf intensity. Redward of this point, the error in the intensity of Hβ increases rapidly with wavelength. Thus in order to compare the pro-
files of different Seyferts in a consistent manner, we must terminate them at $-4000$ and $+4000$ km s$^{-1}$. 

Since the individual profile ratios are still somewhat noisy, we developed a procedure to determine the range of ratio values for an individual Seyfert from 0 to $\pm 4000$ km s$^{-1}$. We determined the minimum ratio value by averaging over the values at radial velocities within 200 km s$^{-1}$ of zero. We determined the maximum values by fitting a line to the profile ratios between $\pm 2000$ and $\pm 4000$ km s$^{-1}$, and finding the values of the line at $-4000$ and $+4000$ km s$^{-1}$. Most of the profile ratios are fairly symmetric, so we averaged the two ratio values at $-4000$ and $+4000$ km s$^{-1}$ to obtain a final maximum value.
Chapter VI

INTERPRETATION OF THE PROFILE RATIOS

6.1 RELATION TO PROFILE WIDTHS

Shuder (1982, 1984) averages his profile ratios by normalizing the velocity scale in each object to the full width at zero intensity (FWZI) of Hα in that galaxy. In other words, he implicitly assumes that the radial velocity that corresponds to a certain value of Hβ/Hα scales with the width of the Hα profile. We will test this assumption with our high signal-to-noise data, which allow us to consider the properties of profile ratios for individual Seyferts.

In Figure 17 we see an unexpected result: the Hβ/Hα profile ratios of Mrk 79 and Mrk 335, plotted on the same velocity and intensity scales, are similar, in spite of the fact that the width (FWHM) of the Hβ profile in Mrk 79 is three times greater than the width of the Hβ profile in Mrk 335. If we had scaled the profiles of Mrk 335 to the same width as the profiles of Mrk 79, the Hβ/Hα ratio of Mrk 335 would have appeared to rise much more slowly with radial velocity than the Hβ/Hα ratio of Mrk 79.
Figure 18 gives another way to demonstrate this point for all nine Seyfert 1 galaxies. Here we plot the FWHM of Hβ versus the range in Hβ/Hα values from the minimum value at zero km s⁻¹ to the average of the maximum values at -4000 and +4000 km s⁻¹. If the radial velocity that corresponds to a certain value of Hβ/Hα scales with the width of the profiles, then we would expect to see the range in Hβ/Hα decrease with the FWHM of Hβ, since we are sampling much less of the total velocity range in the broader profiles. However, Figure 18 demonstrates that there is no trend in the range of Hβ/Hα with profile width. Thus Shuder's method of normalizing the velocity scale to the FWHM of Hα is an inappropriate way to compare the profile ratios of different Seyferts.

The range in Hβ/Hα values over this fixed velocity interval is fairly similar among most Seyferts, and is not a function of the profile width. This is actually evidence that the BLR is spherically symmetric. Consider, for example, a BLR that is in the form of a rotating disk that is initially edge-on to the observer's line of sight. If the plane of the disk is then tilted with respect to the line-of-sight, the Hα and Hβ profiles decrease in width by the same factor, as does the radial velocity that corresponds to a certain Hβ/Hα ratio. We observe however that the radial velocity that corresponds to a certain Hβ/Hα ratio
Figure 17: Hβ/Hα profile ratios for two Seyfert 1 galaxies. The histogram plot is the profile ratio of Mrk 79 and the smooth plot is the profile ratio of Mrk 335.
Figure 18: The FWHM of Hβ plotted against the range in Hβ/Hα.
is roughly constant among Seyferts with different profile widths. Thus for a collection of rotating disks, the disks at greater inclinations must have \( \text{H}\beta/\text{H}\alpha \) ratios that increase much more slowly with actual rotational velocity to match the observations, which is of course absurd. Therefore the BLR is spherically symmetric, since this argument is valid for any non-spherical geometry that is utilized to explain the wide range in observed profile widths as an aspect effect.

Arguments have been put forth in favor of spherical symmetry based on the incompatibility of profiles from rotating disk models with observed profiles (Shields 1978; Capriotti, Foltz, and Byard 1980; Mathews 1982a). However, recent models incorporating turbulent rotating disks have been more successful in matching observed profiles (van Groningen 1983). There are several arguments for spherical symmetry that do not depend on the profile shapes:

1. There is no evidence for a correlation between the axial ratio of the disk of the Seyfert host galaxy and the width of the broad lines (Keel 1980; Simkin, Su, and Schwarz 1980). However, there are reasons to believe that the inclination of the BLR disk does not have to be the same as the inclination of the host galaxy disk (Tohline and Osterbrock 1982).
2. The distribution of the FWZI of Seyfert broad lines is inconsistent with the expected distribution due to a collection of rotating disks (Osterbrock 1977). In particular, there are no Seyfert 1 galaxies with very narrow permitted lines. This argument is not valid if the rotating disks are very turbulent (Osterbrock 1978c, 1979).

3. X-ray observations of the active galactic nuclei Cen A (Mushotzky et al. 1978) and NGC 4151 (Holt et al. 1980) show that the ratio of the 7.1 keV Fe K absorption edge to the associated 6.4 keV fluorescent line is consistent with a spherical distribution of BLR material. If the BLR were a face-on disk, the emission feature would be much more prominent and if the BLR were an edge-on disk the absorption feature would be much more prominent.

Although there are objections to the first two arguments given, the third argument and our own results support the view that the BLR is indeed spherically symmetric.

6.2 RELATION_TO_LUMINOSITY

Shuder (1982, 1984) claims that the Balmer line profiles are more uniform in higher luminosity Seyfert 1 galaxies and QSOs. He arrives at this result by separating the Seyfert 1 galaxies and QSOs into three luminosity classes and
averaging the profile ratios in each class. He finds that the average Hβ/Ha profile ratio for the low luminosity objects increases by a greater factor from the core to the wings than the average ratio for the intermediate luminosity objects, which increases by a greater factor than the average ratio for the high luminosity objects.

We will test this result by determining the nonthermal continuum luminosity at 4861 Å from the observed flux, the stellar fraction, and the redshift of each galaxy. In determining the luminosities we assume that H₀ = 75 km s⁻¹ Mpc⁻¹ and that q₀ = 1. We can estimate the errors in the relative luminosities by comparing the fluxes of the red and blue scans of a given Seyfert, which were taken on different nights. On average, the flux of the red scan differs from that of the blue scan by 20%, and the maximum difference is 40%. These errors are not very significant for this analysis, since the luminosity ranges by a factor of ~100 in our collection of Seyferts.

We present in Figure 19 a plot of the log of the nonthermal continuum luminosity at 4861 Å versus the range in the Hβ/Ha ratio. Although there is some variation in the range of Hβ/Ha from one Seyfert to the next, there is no correlation with luminosity. Thus we do not agree with Shuder's claim that the Balmer profiles become more uniform with increasing luminosity.
We do not know the reason for the discrepancy between our results and the results of Shuder. His range in luminosities coincides with ours, except that his objects extend to higher luminosities by about an order of magnitude. However, there are problems with Shuder's analysis of the data:

1. He normalizes the velocity scale for the profile ratios in each object to the full width at zero intensity of the Hα profile in that object. We have shown that this method is inappropriate.

2. He includes the ratios in the far wings in his analysis. We have shown that there are large systematic errors in the ratios at radial velocities greater than 4000 - 6000 km s⁻¹.

Thus we believe that Shuder's claim that the Balmer profiles are more uniform in higher luminosity objects is suspect, even though his sample contains a larger range in luminosity than ours.

There have been claims that the broad-line profiles of different emission lines in high-redshift, high-luminosity QSOs are the same to within the observational uncertainties (Baldwin and Netzer 1978; Richstone, Ratnatunga, and Schaeffer 1980). Studies of QSOs at higher resolution and signal-to-noise, however, conclude that there are substantial profile differences among different lines. In partic-
Figure 19: The nonthermal luminosity plotted against the range in $\frac{H_\beta}{H_\alpha}$.
ular, the La profile normally has stronger wings and a sharper peak than the C IV λ1549 profile (Wilkes and Carswell 1982; Wilkes 1984).

In order to proceed further with our analysis, we must use the results from recent photoionization models. The most sophisticated treatment of the variation in line ratios with the physical conditions in the BLR is by Kwan (1984). Kwan finds that for a given nonthermal continuum energy distribution, the Hβ/Hα ratio is principally a function of the ionizing flux incident on a BLR cloud, although it also depends weakly on the number density and column density. The He I/Hβ ratio is a strong function of the ionizing flux and is almost independent of the other parameters. In all of our Seyferts, with the possible exception of NGC 5548, these ratios increase with radial velocity; thus the BLR clouds closer to the nonthermal continuum source must have higher velocities on average.

The range in Hβ/Hα from 0 to ±4000 km s⁻¹, averaged over all of our Seyferts, is 0.22 to 0.42. If this ratio continues to increase with radial velocity past ±4000 km s⁻¹, then the maximum value of Hβ/Hα in the BLR may be much greater than 0.42, since some of our Hα profiles have wings that extend out to at least ±10,000 km s⁻¹. Kwan's calculated Hβ/Hα ratios as a function of the ionizing flux range from 0.1 to 0.37. It is apparent that these calculations
must be extended to higher fluxes before combined photoionization and kinematic models can be used to match the observed $H\beta/H\alpha$ profile ratios.

If we assume that the observed increase in $H\beta/H\alpha$ with radial velocity is entirely due to an increase in the ionizing flux, we can investigate the size of BLR. We must keep in mind, however, that our results are photoionization model dependent. In the past, it was realized from photoionization models that the ionization parameter and the electron density are fairly similar among the broad line regions of AGN. The ionizing flux, which is proportional to the product of the ionization parameter and the density, is therefore similar among the broad line regions, and the size of the BLR must scale with the square root of the luminosity. We can elaborate on this idea by again considering Figure 19, where we see that the range in $H\beta/H\alpha$, and therefore the range in ionizing fluxes, is similar among most Seyfert 1 galaxies. Thus, to a rough approximation, the radial extent of that part of the BLR characterized by velocities from 0 to $\pm 4000$ km s$^{-1}$ scales with the square root of the nonthermal continuum luminosity.

The fluxes that correspond to our average minimum and maximum values of $H\beta/H\alpha$ can be estimated from Kwan's graph. The ratio of the maximum to minimum flux is $\sim 25$, which means that the outer radius of the BLR is at least $\sim 5$ times
greater than the inner radius. This estimate is an extreme lower limit to the relative extent of the BLR, because the minimum value of Hβ/Hα at the radial velocity of 0 km s⁻¹ receives contributions from clouds traveling at space velocities perpendicular to our line-of-sight. Also, as discussed previously, the Hβ/Hα ratio for clouds traveling at velocities greater than 4000 km s⁻¹ may be much higher than the maximum we quote. In any case, it is clear that the BLR is not a thin spherical shell.

If Hβ/Hα is a good indicator of the ionizing flux on a BLR cloud, as the models of Kwan (1984) suggest, then the size of the BLR determined from Hβ/Hα should at least be consistent with the size determined from more direct methods. Cherepashchuk and Lyutyi (1973) find from variability studies that the BLR of NGC 3516 has a size of 15-30 light days. We can calculate a model dependent lower limit to the size of the BLR in NGC 3516 from the Hβ/Hα minimum value of 0.23. From the graph of Kwan (1984), we obtain the flux corresponding to this value. We then use the nonthermal continuum energy distribution assumed for Kwan's models (Kwan and Krolik 1981) and our luminosity at 4861 Å to determine a lower limit to the size of the BLR in NGC 3516. We find that the size of the BLR in NGC 3516 is <0.025 pc (~30 light days), which is consistent with the measurements of Cherepashchuk and Lyutyi (1973).
6.3 **SUMMARY**

We obtained high signal-to-noise spectra of Seyfert 1 galaxies to test Shuder's claim that $\text{H}\beta/\text{H} \alpha$ and He I $\lambda 5876/\text{H}\beta$ increase with radial velocity (Shuder 1982, 1984). We considered three effects that might contaminate the profiles in such a way as to weaken the core or strengthen the wings of the H\beta profile relative to the H\alpha profile:

1. We find that stellar absorption features from the host galaxy of a low-luminosity Seyfert can significantly lower the peak of the H\beta profile. Also, stellar contamination can introduce considerable structure and asymmetries into the profiles of H\beta, H\gamma, and He I $\lambda 5876$.

2. Emission from lines other than H\beta strengthen the red wing of the observed H\beta profile considerably. We give evidence that Fe II is not the only species that contributes to the shelf of emission, and that at least one more species (probably broad [O III]) contributes as well.

3. We find that H\alpha is at a better velocity resolution than H\beta in our spectra, which leads to a weaker core for the observed H\beta profile.

Each of the effects that we considered can alter the profile ratios in the core or the wings by 10-20\% at most. Correction for these effects cannot change the observed
increase in $\text{H}_\beta/\text{H}_\alpha$ and $\text{He I}/\text{H}_\beta$ with radial velocity. The change in these line ratios with radial velocity indicates that both the physical conditions and the cloud velocity change in a systematic fashion across the BLR.

From the broad $\text{[C III]}/\text{H}_\beta$ ratio, we determine that the electron density in the BLR is of order $10^9 \text{ cm}^{-3}$. However, there is probably a wide range of densities in the BLR and this value probably represents some sort of average. We also find that the $\text{H}_\beta/\text{H}_\alpha$ profile ratio extends to higher values than those calculated by Kwan (1984) as a function of the ionizing flux incident on a BLR cloud. Therefore, existing photoionization calculations should be extended to a greater range of densities and ionizing fluxes.

From a comparison of profile ratios for individual Seyfert 1 galaxies, we can put restrictions on BLR kinematic models. The BLR clouds are in a spherical distribution around the nonthermal continuum source, since there is no observed correlation of the range in $\text{H}_\beta/\text{H}_\alpha$ with profile width. If $\text{H}_\beta/\text{H}_\alpha$ is primarily a function of the ionizing flux, as the models of Kwan (1984) suggest, then clouds closer to the continuum source must have higher velocities on average. Finally, the large range in $\text{H}_\beta/\text{H}_\alpha$ and $\text{He I}/\text{H}_\beta$ for a given Seyfert 1 galaxy suggests that the BLR is not a thin spherical shell.
Obviously, more than one type of kinematic model can satisfy the above requirements. For example, in the recent models of Mathews (1982b), the clouds undergo radiatively driven outflow. Clouds that form close to the continuum source are accelerated to high velocities and travel short distances, whereas clouds that form farther from the continuum source are accelerated to shorter velocities and travel greater distances. However, in the models of Carroll and Kwan (1985), the clouds undergo gravitational motion in orbits that are essentially parabolic. In these models, the velocity also decreases with increasing distance from the nonthermal continuum source.

Further work on profile ratios of Seyfert 1 galaxies and QSOs is definitely needed. On the observational side, profiles of Hα, Hβ, and He I λ5876 should be obtained for a wider range of luminosities and profile widths to further investigate the results we have given. Also, high-quality profiles of emission lines in the ultraviolet are needed, since it is apparent from recent photoionization models (Kwan 1984) that ultraviolet line ratios are needed to evaluate such physical conditions in the BLR as number density and column density.

Finally, in order to get more information out of the observed profile ratios, photoionization models should be combined with various kinematic models. From the photoion-
ization models it is possible to determine the dependence of line emissivities on the physical conditions. This information can be used in a given kinematic model to determine profiles for different lines. The calculated profiles and profile ratios from various kinematic models can then be compared to those observed to determine if any given kinematic model is favored.
Appendix A

BROAD-LINE PROFILES

Figure 20: Broad emission line profiles of Seyfert 1 galaxies. The lower plot has been corrected for all contamination effects. The upper plot has been corrected for stellar contamination and velocity resolution differences, but not for emission-line contamination.
Figure 20: (continued)

RELATIVE FLUX

NGC 3516

RELATIVE FLUX

NGC 3516
Figure 20: (continued)

RELATIVE FLUX

NGC 4593
Ha

VEL OCITY

RELATIVE FLUX

NGC 4593
Hβ
Figure 20: (continued)

RELATIVE FLUX

NGC 5548

Hα

RELATIVE FLUX

NGC 5548

Hα
Figure 20: (continued)

Relative Flux

NGC 7469

Velocity

NGC 7469

Hα

Hβ
RELATIVE FLUX

Figure 20: (continued)
Figure 20 (continued):  

RELATIVE FLUX  

![Graph showing velocity and relative flux over a range of values with labels HE I λ5876 and MK II 110.]

RELATIVE FLUX  

![Graph showing velocity and relative flux over a range of values with labels HE I λ5876 and MK II 79.]

100
Figure 20 (continued)

RELATIVE FLUX

VELCITY

Hα
MRK 110

RELATIVE FLUX

VELCITY

Hβ
MRK 110
Figure 20 (continued)

**Relative Flux vs. Velocity**

**Hα**

**MRK 335**

**Hβ**

**MRK 335**

V E L O C I T Y

R E L A T I V E F L U X
Figure 20: (continued)
Figure 20: (continued)
Appendix B

PROFILE RATIOS

Figure 21: Profile ratios of Seyfert 1 galaxies. The Hg/Hα profile ratio is given for nine Seyfert 1 galaxies and the He I λ5876/Hg profile ratio is given for five Seyfert 1 galaxies.
Figure 21: (continued)
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BIBLIOGRAPHY


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