ANALYSIS OF OPTICAL Fe$^\text{ii}$ EMISSION IN A SAMPLE OF ACTIVE GALACTIC NUCLEUS SPECTRA

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ABSTRACT

We present a study of optical Fe$^\text{ii}$ emission in 302 active galactic nuclei (AGNs) selected from the Sloan Digital Sky Survey. We group the strongest Fe$^\text{ii}$ multiplets into three groups according to the lower term of the transition (b$^4$F, a$^6$S, and a$^4$G terms). These approximately correspond to the blue, central, and red parts, respectively, of the “iron shelf” around H$\beta$. We calculate an Fe$^\text{ii}$ template that takes into account transitions into these three terms and an additional group of lines, based on a reconstruction of the spectrum of I Zw 1. This Fe$^\text{ii}$ template gives a more precise fit of the Fe$^\text{ii}$ lines in broad-line AGNs than other templates. We extract Fe$^\text{ii}$, H$\alpha$, H$\beta$, [O iii], and [N ii] emission parameters and investigate correlations between them. We find that Fe$^\text{ii}$ lines probably originate in an intermediate line region. We note that the blue, red, and central parts of the iron shelf have different relative intensities in different objects. Their ratios depend on continuum luminosity, FWHM H$\beta$, the velocity shift of Fe$^\text{ii}$, and the H$\alpha$/H$\beta$ flux ratio. We examine the dependence of the well-known anti-correlation between the equivalent widths of Fe$^\text{ii}$ and [O iii] on continuum luminosity. We find that there is a Baldwin effect for [O iii] but an inverse Baldwin effect for the Fe$^\text{ii}$ emission. The [O iii]/Fe$^\text{ii}$ ratio thus decreases with $L_{\lambda\sim5100}$. Since the ratio is a major component of the Boroson & Green Eigenvector 1 (EV1), this implies a connection between the Baldwin effect and EV1 and could be connected with AGN evolution. We find that spectra are different for H$\beta$ FWHMs greater and less than $\sim3000$ km s$^{-1}$, and that there are different correlation coefficients between the parameters.

Key words: atomic processes – galaxies: active – quasars: emission lines

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1. INTRODUCTION

Optical Fe$^\text{ii}$ (\$\lambda\lambda4400–5400\$) emission is one of the most interesting features in active galactic nucleus (AGN) spectra. The emission arises from numerous transitions of the complex Fe$^\text{ii}$ ion. Fe$^\text{ii}$ emission is seen in almost all type-1 AGN spectra and it is especially strong in narrow-line Seyfert 1s (NLS1s). It can also appear in the polarized flux of type-2 AGNs and location of the Fe$^\text{ii}$ when a hidden broad-line region (BLR) can be seen. Origin (NLS1s). It can also appear in the polarized flux of type-2 AGNs spectra and it is especially strong in narrow-line Seyfert 1s (NLS1s). It can also appear in the polarized flux of type-2 AGNs.

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Wills 1983), and (d) fluorescent excitation by the Ly$\beta$ as the broad H$\beta$ lines (Penston 1988; Verner et al. 1999).

The relative strength of the Fe$^\text{ii}$ lines correlates with the soft X-ray slope, but anti-correlates with X-ray luminosity (Wilkes et al. 1987; Boller et al. 1996; Lawrence et al. 1997). Strong optical Fe$^\text{ii}$ emission is usually associated with strong IR luminosity (Low et al. 1989; Lipari et al. 1993), but it is anti-correlated with IR color index $\alpha(60,25)$ (Wang et al. 2006).

Many correlations have been observed between Fe$^\text{ii}$ and other emission lines. Boroson & Green (1992) give a number of correlations between the equivalent width (EW) of Fe$^\text{ii}$ and properties of the [O iii] and H$\beta$ lines. The most interesting are the anti-correlations of EW Fe$^\text{ii}$ versus EW [O iii]/EW H$\beta$, EW Fe$^\text{ii}$ versus peak [O iii], EW Fe$^\text{ii}$/EW H$\beta$ versus peak [O iii], and the correlation of EW Fe$^\text{ii}$/EW H$\beta$ versus H$\beta$ asymmetry. An anti-correlation between EW Fe$^\text{ii}$ and FWHM of H$\beta$ has also been found (Gaskell 1985; Zheng & Keel 1991; Boroson & Green Souffrin et al. 1980; Zhang et al. 2006), (c) in a region that can be heated by shocks or from an inflow, located between BLR and narrow-line region (NLR)—the so-called the intermediate line region (ILR; Marziani & Sulentic 1993; Popović et al. 2004, 2007, 2009; Hu et al. 2008b; Kuehn et al. 2008), and (d) and in the shielded, neutral, outer region of a flattened BLR (Gaskell et al. 2007; Gaskell 2009).

3. It has long been established that the Fe$^\text{ii}$ emission is correlated with the radio, X-ray, and IR continua. Fe$^\text{ii}$ lines are stronger in spectra of radio-quiet (RQ) AGNs than in radio-loud (RL) objects (Osterbrock 1977; Bergeron & Kunth 1984). But, if we consider RL AGNs, Fe$^\text{ii}$ emission is stronger in core dominant (CD) AGNs than in lobe dominant (LD) AGNs (Setti & Wolter 1991; Joly 1991). The relative strength of the Fe$^\text{ii}$ lines correlates with the soft X-ray slope, but anti-correlates with X-ray luminosity (Wilkes et al. 1987; Boller et al. 1996; Lawrence et al. 1997). Strong optical Fe$^\text{ii}$ emission is usually associated with strong IR luminosity (Low et al. 1989; Lipari et al. 1993), but it is anti-correlated with IR color index $\alpha(60,25)$ (Wang et al. 2006).

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These correlations dominate the first eigenvector of the principal component analysis of Boroson & Green (1992; hereinafter EV1). Correlations between EV1 and some properties of C iv λ1549 lines have also been pointed out (Baskin & Laor 2004). With increasing continuum luminosity, the EW of the C iv lines decreases (the so-called Baldwin effect, Baldwin 1977; Wang et al. 1995), while the blueshift of the C iv line and the EW of Fe ii increase. Recently, Dong et al. (2009) have found the Baldwin effect to be related to EV1. Fe ii lines are usually strong in AGN spectra with low-ionization broad absorption lines (BALs; Harting & Baldwin 1986; Boroson & Meyers 1992).

Searching for a physical cause of these correlations may help in understanding of the origin of Fe ii emission. Some of physical properties which may influence these correlations are the Eddington ratio \( (L/L_{\text{Edd}}; \text{Boroson & Green 1992; Baskin & Laor 2004}) \), black hole mass \( (M_{\text{BH}}) \), and inclination angle (Miley & Miller 1979; Wills & Browne 1986; Marziani et al. 2001).

In addition to these properties, Fe ii emission strength may vary with evolution of AGNs. For example, Lipari & Terlevich (2006) have explained some properties of AGN (as BALs, Fe ii strength, radio properties, emission line width, luminosity of narrow lines, etc.) by an "evolutionary unification model." In this model, accretion arises from the interaction between nuclear starbursts and the supermassive black hole. This would mean that not only the orientation, but also the evolutionary state of an AGN influence its spectral properties. Thus, young AGNs have strong Fe ii, BALs, and weak radio emission, also the NLR is compact and faint, and broad lines are relatively narrow. In contrast with this, old AGNs have weak Fe ii, no BALs, strong radio emission with extended radio lobes, the NLR is extended and bright, and the broad lines have greater velocity widths.

In this paper, we investigate the Fe ii emitting region by analyzing the correlations between the optical Fe ii lines and the other emission lines in a sample of 302 AGNs from the Sloan Digital Sky Survey (SDSS). To do this we construct an Fe ii template. The strongest Fe ii multiplets within the 4400–5500 Å range are sorted into three groups, according to the lower terms of the transitions: 3d^{6}(F2)4s^{2}4F, 3d^{6}(4S5S_{1/2})s^{2}4S, and 3d^{6}(4G)4s^{2}4G (which we will hereinafter refer to as the F, S, and G groups of lines). The F group mainly contains the lines from the Fe ii multiplets 37 and 38 and describes the blue part of the Fe ii shelf relative to H\(\beta\). The S group of lines describes the part of Fe ii emission under H\(\beta\) and [O iii] and contains lines from multiplets 41, 42, and 43 Fe ii. Finally, the G group contains lines from multiplets 48 and 49, and describes the red part of the Fe ii shelf. A simplified Grotrian diagram of these transitions is shown in Figure 1. We separately analyze their relationships with other lines in AGN spectra (H\(\beta\), [O iii], H\(\alpha\), [N ii]). In this way, we try to connect details of the Fe ii emission with physical properties of the AGN emission regions in which these lines arise. Each of the Fe ii multiplet groups has specific characteristics, which may be reflected in a different percent of correlations with other lines, and gives us more information about the complex Fe ii emission region.

The paper is organized as follows: in Section 2, we describe the procedure of sample selection and details of analysis; our results are presented in Section 3; in Section 4 we give discussion of obtained results, and finally in Section 5 we outline our conclusions.

Figure 1. Top: Grotrian diagram showing the strongest Fe ii transitions in the 4400–5500 Å region. Middle: Lines are separated into three groups according to the lower level of transition: F (dashed line), S (solid line), and G (dash-dotted line). Bottom: the lines from the three line groups (solid line) and lines measured from I Zw 1 (represented with dots).

2. THE SAMPLE AND ANALYSIS

2.1. The AGN Sample

Spectra for our sample are taken from the seventh data release (Abazajian et al. 2009) of the SDSS. For the purposes of the work, we chose AGNs with the following characteristics.

1. High signal-to-noise ratio \( (S/N > 20) \).
2. Good pixel quality (profiles are not affected by distortions due to bad pixels on the sensors, the presence of strong foreground or background sources).
3. High-redshift confidence \( (z_{\text{Conf}} > 0.95) \) and with \( z \leq 0.7 \) in order to cover the optical Fe ii lines around H\(\beta\) and [O iii] lines.
4. Negligible contribution from the stellar component. We controlled for this by having the EWs of typical absorption lines be less than 1 Å (EW CaK 3934 Å, Mg 5177 Å, and H\(\delta\) 4102 Å > −1).4 Because of this it was not necessary to remove a host galaxy starlight contribution.
5. Presence of the narrow [O iii] and the broad H\(\beta\) component (FWHM H\(\beta\) > 1000 km s\(^{-1}\)).

We found 497 AGNs using the mentioned criteria. However, on inspection of the spectra we found that in some of them...

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4 For some objects we were able to find estimates of the stellar component in the literature and to confirm that the host galaxy fraction is indeed small in our sample (see Appendix A).
the Fe II line emission is within the level of noise and could not be properly fitted, so we excluded these objects from further analysis (see Appendix A). As a result, our final sample contains 302 spectra, from which 137 have all Balmer lines, and the rest are without the Hα line (due to cosmological redshifts). The sample distribution by continuum luminosity (λ5100) and by cosmological redshift is given in Figure 2. Corrections for Galactic extinction were made using an empirical selective extinction function computed for each spectrum on the basis of Galactic extinction coefficients given by Schlegel (1998) and available from the NASA/IPAC Extragalactic Database.\(^5\) Finally, all spectra were de-redshifted.

To subtract the continuum, we used the DIPSO software, finding the continuum level by using continuum windows given in the paper of Kuraszkiewicz et al. (2002; see Figure 3). The used continuum windows are 3010–3040 Å, 3240–3270 Å, 3790–3810 Å, 4210–4230 Å, 5080–5100 Å, 5600–5630 Å, and 5970–6000 Å. We used the same procedure to subtract the continuum in all objects. Continuum subtraction may cause systemic errors in the estimation of line parameters and continuum luminosity. We estimated that the error bars are smaller than 5%, especially within the Hα+[N ii] region and in the red part of the “iron shelf.”

We considered two spectral ranges: 4400–5500 Å and 6400–6800 Å. In the first range, dominant lines are the numerous Fe II lines, [O iii] λλ4959, 5007, Hβ and He II λ4686, and in the second range, Hα and [N ii] λλ6548, 6583.

To investigate correlations between the Fe II multiplets and other lines in spectra, we fit all considered lines with Gaussians. The optical Fe II lines were fitted with a template calculated as described in the next section.

### 2.2. The Fe II (λλ4400–5500) Template

A number of authors have created an Fe II template in the UV and optical range (see Vestergaard & Wilkes 2001, and references therein). Boroson & Green (1992) applied an empirical template by removing all lines which are not Fe II, from the spectrum of I Zw 1. Similarly, Veron-Cetty et al. (2004) constructed an Fe II template by identifying systems of broad and of narrow Fe II lines in the I Zw 1 spectrum, and measuring their relative intensities. Dong et al. (2008) improve on that template by using two parameters of intensity—one for the broad and the other for the narrow Fe II lines. All these empirical templates are defined by the line width and the line strength, implying that relative strengths of the lines in the Fe II multiplets are the same in all objects.

In theoretical modeling, significant effort has been made to calculate the iron emission by including a large number of Fe II atomic levels, going to high energy (Verner et al. 1999; Sigut & Pradhan 2003; Collin-Souffrin et al. 1980; Bruhweiler & Verner 2008). Bruhweiler & Verner (2008) calculated Fe II emission

\(^5\) [http://nedwww.ipac.caltech.edu/](http://nedwww.ipac.caltech.edu/)
using the CLOUDY code and the 830 level Fe\textsc{ii} model. In this model, energies go up to 14.6 eV, producing 344,035 atomic transitions. For their calculations they used solar abundances for a range of physical conditions such as the flux of ionizing photons [\text{F}_\text{H}], hydrogen density [\text{n}_\text{H}], and microturbulence [\text{\xi}].

Using existing Fe\textsc{ii} templates, we found that empirical and theoretical models can generally fit NLSy1 Fe\textsc{ii} lines well, but that in some cases of spectra with broader H\textbeta~lines, the existing models did not provide as good fit.

One of the problems in the analysis of Fe\textsc{ii} emission is that it consists of numerous overlapping lines. This makes the identification and determination of relative intensities very difficult. Therefore, the list of Fe\textsc{ii} lines used for the fit of the Fe\textsc{ii} emission, as well as their relative intensities, is different in different models (Veron-Cetty et al. 2004; Bruhweiler & Verner 2008). Also, there is significant disagreement in values of oscillator strengths in different atomic data sources (Fuhr et al. 1981; Giridhar & Ferro 1995; Kurucz 1990).

To investigate the Fe\textsc{ii} emission, we made an Fe\textsc{ii} template taking into account the following: (1) the majority of multiplets dominant in the optical part (\(\lambda\lambda4400–5500\)), whose lines can be clearly identified in AGN spectra, have one of the three specific lower terms of their transitions: \(F, S,\) or \(G;\) and (2) beside these lines there are also lines whose origin is not well known but which presumably originate from higher levels.

We constructed an Fe\textsc{ii} template consisting of 50 Fe\textsc{ii} emission lines, identified as the strongest within the 4400–5500 Å range. Thirty-five of them are sorted into three line groups according to the lower term of their transition (\(F, S,\) and \(G\)). The \(F\) group consists of 19 lines (mainly multiplets 37 and 38) and dominates in the blue shell of the iron template (4400–4700 Å). The \(S\) group consists of five lines (multiplets 41, 42, and 43) and describes the Fe\textsc{ii} emission covering the [O\textsc{iii}] \(\beta\) region of the spectrum and some of emission from the red Fe\textsc{ii} bump (5150–5400 Å), and the \(G\) lines (11 lines from multiplets 48 and 49) dominate in the red bump (5150–5400 Å; see Figure 1).

We assumed that the profiles of each of lines can be represented by a Gaussian, described by width \((W)\), shift \((d)\), and intensity \((I)\). Since all Fe\textsc{ii} lines from the template probably originate in the same region, with the same kinematical properties, values of \(d\) and \(W\) are assumed to be the same for all Fe\textsc{ii} lines in the case of one AGN.

Since the population of the lower term is influenced by transition probabilities and excitation temperature, we assumed that the relative intensities between lines within a line group (\(F, S,\) or \(G\)) can be obtained approximately from

\[
\frac{I_1}{I_2} = \left(\frac{\lambda_2}{\lambda_1}\right)^3 \frac{f_1}{f_2} \frac{g_1}{g_2} e^{-(E_1-E_2)/kT},
\]

where \(I_1\) and \(I_2\) are the intensities of lines with the same lower term, \(\lambda_1\) and \(\lambda_2\) are the wavelengths of the transition, \(g_1\) and \(g_2\) are the statistical weights for the upper energy levels, \(f_1\) and \(f_2\) are the oscillator strengths, \(E_1\) and \(E_2\) are the energies of the upper levels of transitions, \(k\) is the Boltzmann constant, and \(T\) is the excitation temperature. Details can be found in Appendix C. The excitation temperature is the same for all transitions in the case of partial local thermodynamic equilibrium (LTE) (see Griem 1997), but as it is shown in Appendix C, Equation (1) may also be used in some non-LTE cases.

\[6\] Here we used \(W = \frac{\lambda_0}{c}, d = \frac{\Delta \lambda}{\lambda_0}\), where \(W_D = \sigma \sqrt{2}\) is the Doppler width, \(\Delta \lambda\) is the shift, and \(\sigma\) is the velocity dispersion.

\[7\] http://www.pmp.uni-hannover.de/cgi-bin/ssi/test/kurucz/sekur.html

Figure 4. Distribution of the excitation temperatures for the sample of 302 AGNs. Temperatures are obtained by fits using Equation (1). The mean value and dispersion are shown in the figure.

Lines from the three above mentioned groups explain about 75% of the Fe\textsc{ii} emission in the observed range (4400–5500 Å), but about 25% of Fe\textsc{ii} emission cannot be explained with permitted lines for which the excitation energies are close to the lines of the three groups. The missing Fe\textsc{ii} emission is around \(~4450 \text{ Å}, \sim 4630 \text{ Å}, \sim 5130 \text{ Å},\) and \(~5370 \text{ Å}.\)

There are some indications that fluorescence processes may have a role in producing some Fe\textsc{ii} lines (Verner et al. 1999; Hartman & Johansson 2000). Processes like self-fluorescence, continuum fluorescence, or Ly\alpha and Ly\beta~pumping could supply enough energy to excite the Fe\textsc{ii} lines with a high energy of excitation, which could provide one of the explanations for emission within these wavelength regions. To complete the template for approximately 25% of missing Fe\textsc{ii} flux, we selected 15 lines from the Kurucz database\(^7\) with wavelengths close to those of the extra emission, upper level excitation energies of up to \(~13 \text{ eV},\) and strong oscillator strengths. We measured their relative intensities in I Zw 1 which has a well-studied spectrum (Veron-Cetty et al. 2004), with strong and narrow Fe\textsc{ii} lines. Relative intensities of these 15 lines were obtained by making the best fit of the I Zw 1 spectrum with the Fe\textsc{ii} lines from the \(F, S,\) and \(G\) line groups. The extra lines are represented in Figure 1 (bottom), with a dotted line.

Our template of Fe\textsc{ii} is described by seven free fitting parameters; the first six being width, shift, and four parameters of intensity (for the \(F, S,\) and \(G\) line groups and for the lines with relative intensities obtained from I Zw 1). The seventh parameter is the excitation temperature included in the calculation of relative intensities within \(F, S,\) and \(G\) line groups.

We found that for the majority of objects, the excitation temperature obtained from our fit is within the range of 9000 K–11,000 K (see Figure 4), which agrees well with theoretical predictions (Collin & Joly 2000). However, as it can be seen in Equation (1), our fit is not very sensitive to the temperature, especially for \(T > 8000 \text{ K}.\) Equation (1) is also very approximate, so estimated temperatures should be treated with caution.

To estimate the error in the excitation temperature, we found our best fit for a number of objects. We then changed only the
dispersion in temperature at 0.1 (excitation temperature while keeping the other fit parameters bars that were mostly within the range (Table 1). For the 15 lines for which relative intensities were (1) Fuhr et al. 1981; (2) Giridhar & Ferro 1995; (3) NIST Atomic Spectra Database (http://physics.nist.gov/PhysRefData/ASD/); (4) Kurucz1990; (5) http://www.pmp.uni-hannover.de/cgi-bin/ssi/test/kurucz/sekur.html. Notes. In the first column are wavelengths (in air), in the second multiplet numbers (Giridhar & Ferro 1995), in the third are terms of transitions, in the fourth are $gf$ values used for the template calculation, in the fifth are the references for the source of oscillator strengths, and in the 6th–8th columns are relative intensities, calculated for $T = 5000 \, \text{K}, 10,000 \, \text{K},$ and $15,000 \, \text{K}.$ Intensities of lines from the $F,$ $S,$ and $G$ groups are normalized to intensities of the $\lambda 4549,474, \lambda 5018,44, \text{and } \lambda 5316.4 \text{lines (respectively).}$ References. (1) Fuhr et al. 1981; (2) Giridhar & Ferro 1995; (3) NIST Atomic Spectra Database (http://physics.nist.gov/PhysRefData/ASD/); (4) Kurucz 1990; (5) http://www.pmp.uni-hannover.de/cgi-bin/ssi/test/kurucz/sekur.html.

The wavelengths of the 50 template lines are presented in Tables 1 and 2. For the 35 lines from the three line groups we give multiplet names, configurations of the transitions generating those lines, oscillator strengths, and the relative intensities. The intensities have been calculated using the Equation (1) for excitation temperatures $T = 5000, 10,000,$ and $15,000 \, \text{K}.$ For the 15 lines for which relative intensities were measured in I Zw 1, we give wavelengths, configurations, and oscillator strengths taken from Kurucz database, as well as their measured relative intensities (Table 2).

The purpose of dividing the Fe II emission into four groups is to investigate the correlations between the iron lines that arise from different multiplets and some spectral properties, and to compare them with results obtained for the total Fe II within the observed range. Also, a template that has more parameters may give a better fit, since relative intensities among Fe II lines can be different even in the similar AGN spectra, as is, for example, the case for spectra of I Zw 1 and Mrk 42 (as, e.g., Phillips 1978b).

We applied this template to our sample of 302 AGNs from SDSS database, and we compare it with other theoretical and empirical models (see Appendix B). We found that the template
fits Fe II emission very well (Figure 23 and Figure 24). In the cases when the FeII emission of an object has different properties from I Zw 1, small disagreements are noticed in the lines for which the relative intensity was obtained from I Zw 1. However, the FeII emission in these objects shows larger disagreement with the empirical and theoretical models considered in Appendix B (see Figure 25). Although our FeII template has more free parameters than other templates used for fitting the FeII emission, it enables more precise fits of FeII lines in some AGNs (especially with very broad Hβ line) than the other FeII templates we considered.

2.3. Emission-line Decomposition and Fitting Procedure

We assume that broad emission lines (BELs) arise in two or more emission regions (Brotherton et al. 1994; Popović et al. 2004; Bon et al. 2006, 2009; Ilić et al. 2006), so that their profiles are sums of Gaussians with different shifts, widths, and intensities, which reflect the physical conditions of the emitting regions where the components arise.

For this reason, we fit the emission lines we considered ([O III] λλ4959, 5007, Hβ, He II λ4686, Hα, and [N II] λλ6548, 6583) with a sum of Gaussians, describing one Gaussian with three parameters (width, intensity, and shift from the transition wavelength).

Both lines of the [O III] λλ4959, 5007 doublet originate from the same lower energy level and both have a negligible optical depth since the transitions are strongly forbidden. Taking this into account, we assumed that the [O III] λ4959 and [O III] λ5007 lines have the same emission-line profile. We fit each line of the doublet with either a single Gaussian, or, in the case of a significant asymmetry, with two Gaussians. The Gaussian that describes the [O III] λ4959 has the same width and shift as the one which describes the [O III] λ5007 line, and we took their intensity ratio to be 2.99 (Dimitrijević et al. 2007). [N II] λλ6548, 6583 were fitted using the same procedure, with an intensity ratio of the doublet components of ≈3. The He II λ4686 line was fitted with one broad Gaussian.

To fit the Balmer lines, a number of Gaussian functions were used for each line. It is usually assumed that there are two components for Hα and Hβ: a narrow component representing the NLR, and a broad one representing the BLR. However, the broad emission lines (BELs) are very complex and cannot be properly explained by single Gaussian (which would indicate an isotropic spherical region). Moreover, there are some papers (Brotherton et al. 1994; Corbin & Boroson 1996; Popović et al. 2004; Ilić et al. 2006; Bon et al. 2006, 2009; Hu et al. 2008a) where the broad lines are assumed to be emitted from two kinematically different regions: a “Very Broad Line Region” (VBLR) and an ILR. We therefore tested fitting the broad lines with one and two Gaussians. We found that in most AGNs in our sample, the fit with two Gaussians was significantly better than the fit with one Gaussian.

To apply a uniform model of the line-fitting procedure, we assumed that Balmer lines have three components from the NLR, ILR, and VBLR. We exclude four spectra from the sample in which the Hα line could not be decomposed in this way, so finally our sample contains 133 spectra (from 137) with all Balmer lines that could be analyzed within the 6400–6800 Å range. To check this assumption on the rest of the spectra, we examined the corresponding correlations and found that the luminosities and widths of the NLR, ILR, and VBLR components of Hα are highly correlated with the same parameters of the NLR, ILR, and VBLR components of Hβ.

Wavelength Transitions gf Relative Intensity
4418.957 y 4G4/2−4F3/2 1.45E-02 3.00
4449.616 y 4G5/2−4F3/2 2.58E-02 1.50
4471.273 y 4D3/2−4F3/2 6.40E-03 1.20
4493.529 y 4G10/2−4F9/2 3.74E-02 1.60
4614.551 y 4P9/2−4D7/2 2.69E-03 0.70
4625.481 x 4D1/2−4F3/2 8.51E-03 0.70
4628.786 x 4D3/2−4F3/2 1.83E-02 1.20
4631.873 x 4D3/2−4F3/2 1.34E-02 0.60
4660.593 d 4S2 2G7/2−2G3/2 1.15E-03 1.00
4668.923 x 4D3/2−4F1/2 3.13E-03 0.90
4740.828 y 4P3/2−4F1/2 1.98E-03 0.50
5131.210 y 4P3/2−4D3/2 2.13E-03 1.1
5369.190 e 4D3/2−4D5/2 1.23E-03 1.45
5396.232 e 4D1/2−4D3/2 2.80E-03 0.40
5427.826 b 4G11/2−4F9/2 2.17E-02 1.40

Notes. In the first column are wavelengths (in air), in the second oscillator strengths, and in the third relative intensities measured in I Zw 1.

This is in favor of our three-component decomposition (Table 3). For the 133 objects, which have both Hβ and Hα lines, it can be noticed that 16 spectra have large redshifts of the VBLR Hβ component relative to VBLR Hα, which causes disagreement and reduces the correlation between the VBLR shifts of the rest of objects. Without these 16 objects, Hβ and Hα VBLR components correlate in width and shift, with coefficient of correlation ≈−0.3, P < 0.001. An example of shifts between the Hα and Hβ VBLR components is shown in Figure 5. The AGN SDSS J111603.13 + 020852.2 has its VBLR Hβ component redshifted by ≈4258 km s⁻¹, while shift of the Hα VBLR component is ≈1200 km s⁻¹.

We assume that all narrow lines (and narrow components of the broad lines) originate from the same NLR, and thus expect that these lines will have the same shifts and widths. We therefore took the Gaussian parameters of the shift and width of [O III], [N II], and the NLR components of Hβ and Hα to have the same values.

We separately fit lines from the 4400–5500 Å range (FeII lines, [O III], He II, and Hβ) with 23 free parameters, and lines from the 6400–6800 Å range (Hα and [N II]) with eight free parameters. We applied a χ² minimization routine (Popović et al. 2004) to obtain the best fit. Examples of an AGN spectrum fit in both ranges are shown in Figures 6 and 7.

2.4. Line Parameters

We compared the shifts, widths, EWs, and luminosities of the lines. The shifts and widths were obtained directly from the fit (parameters of width and shift). Luminosities were calculated using the formulae given in Peebles (1993), with adopted cosmological parameters ΩM = 0.27, ΩΛ = 0.73, and Ωb = 0. We adopt a Hubble constant, H₀ = 71 km s⁻¹ Mpc⁻¹. The continuum luminosity was obtained from the average value of the continuum flux measured between 5100 Å (λλ5095–5100 and λλ5100–5105). EWs were measured with respect to the continuum below the lines. The continuum was estimated by subtracting all fitted lines from the observed spectra. Then, the line of interest (or the FeII template), which is fitted separately, is added to the continuum. EWs are obtained by normalizing the lines on continuum level, and by measuring their fluxes (see Figure 8). To determine the full width at half-maximum
3. RESULTS

3.1. The Ratios of Fe II Line Groups versus Other Spectral Properties

Some objects have relative intensities of Fe II lines similar to I Zw 1, while others show significant disagreement, which usually shows up as stronger iron emission in the blue bump (mainly F lines) than one in the red bump (mainly G lines), comparing to I Zw 1. That objects could be fitted well with the template model which assumes that relative intensities between the Fe II lines from different line groups (F, S, and G) are different for different objects.

Difference between the relative intensities of the Fe II lines from different parts of iron shelf (blue, red, and central) can be illustrated well with histograms of distribution of the Fe II group ratio (F/G, F/S, and G/S) for the sample (Figure 10). The average value of the F/G luminosity ratio is 1.44 ± 0.55, of the F/S ratio 1.97 ± 1.05, and of the G/S ratio 1.39 ± 0.46.\textsuperscript{8} We found that the majority of objects have Fe II group ratios close to the average values, but still a significant number of objects are showing a difference since the intensity ratios of Fe II line groups vary in different objects (see Figure 10). The ratios of the Fe II line groups in I Zw 1 are indicated by the vertical dashed lines (F/G = 1.10, F/S = 1.56, and G/S = 1.41).

We analyzed the flux ratios of the Fe II multiplet groups and the total Fe II flux (see histograms in Figure 11), and we found that lines from multiplets 37 and 38 (group F) generally have the largest contribution to the total Fe II emission within the 4400–5500 Å range (about 32%), while group S contributes about 18% and G about 23%. As expected, there are very strong correlations between the EWs of Fe II line groups (Table 4).

Since line intensities and their ratios are indicators of physical properties of the plasma where those lines arise, we have investigated relations among the ratios of Fe II line groups with various spectral properties. A correlation between the FWHM Hβ and the EW Fe II emission has previously been found (Gaskell 1985; Boroson & Green 1992; Sulentic et al. 2009). Consequently, one can expect that FWHM Hβ may be connected with the Fe II line group ratios. We therefore investigated correlations between the ratios of the Fe II groups (F/G, F/S, and G/S) and Hβ FWHM. We excluded the three outliers, which have negligible flux for the S group. As it can be seen in Figure 12 (first panel) there are different trends for spectra with FWHM Hβ less than and greater than \( \sim 3000 \text{ km s}^{-1} \). Therefore, we divided the sample into two sub-samples: 158 objects with FWHM Hβ < 3000 km s\(^{-1}\) and 141 objects with FWHM Hβ > 3000 km s\(^{-1}\) (see Figure 12 and Table 5). A similar subdivision of AGN samples was performed by Sulentic et al. (2002, 2009) and Zamfir et al. (2010), but for FWHM Hβ \( \approx 4000 \text{ km s}^{-1} \) as the limiting FWHM of the subdivision. We found that FWHM Hβ \( \approx 3000 \text{ km s}^{-1} \) is a more appropriate place to divide the objects into two groups, since all objects with strongly redshifted VBLR Hβ component (see Figure 5) belong to the FWHM Hβ > 3000 km s\(^{-1}\) sub-sample. Sulentic et al. (2002) also noticed that AGNs with FWHM Hβ > 4000 km s\(^{-1}\) have a larger redshifted VBLR Hβ (~5000 km s\(^{-1}\)).

In Table 5, we present the correlations between the luminosity ratios of the Fe II line groups and other spectral properties such as FWHM Hβ, Doppler width of Hβ broad components, width and shift of iron lines, and continuum luminosity \( (L_{\lambda_{5100}}) \). They are examined for the total sample and for two sub-samples, divided according to FWHM Hβ, and denoted in Table 5 as (1) for FWHM Hβ < 3000 km s\(^{-1}\) and (2) for Hβ FWHM > 3000 km s\(^{-1}\).

We found a difference in the correlations for those two sub-samples. For the Hβ FWHM > 3000 km s\(^{-1}\) sub-sample (2), all three ratios (F/G, F/S, and G/S) increase as Hβ width increases. On the other hand, for the Hβ FWHM <

\textsuperscript{8} Here we give the averaged ratio value and dispersion.
Figure 6. Spectrum of SDSS J141755.54 + 431155.8 in the 4400–5500 Å region: (A) the observed spectra (dots) and the best fit (solid line). (B) Hβ fit with the sum of three Gaussians representing emission from the NLR, ILR, and VBLR. The [O III] λλ4959, 5007 lines are fitted with two Gaussians for each line of the doublet and Hα λ4686 is fitted with one broad Gaussian. The Fe II template is denoted with a dashed line, and also represented separately in panel C (bottom).

Table 3
Correlations between Widths, Shifts, and Luminosities of the NLR, ILR, and VBLR Components of the Hα and Hβ Lines

| Correlation (Hα and Hβ) | r   | P       | A                   | B                   |
|------------------------|-----|---------|---------------------|---------------------|
| Hα NLR width vs. Hβ NLR width | 0.99 | <0.0001 | 6.19 ± 2.81         | 0.97 ± 0.01         |
| Hα ILR width vs. Hβ ILR width | 0.91 | <0.0001 | 165.37 ± 43.29      | 0.74 ± 0.03         |
| Hα VBLR width vs. Hβ VBLR width | 0.50 (0.42) | <0.0001 | 1863.15 ± 352.50    | 0.54 ± 0.08         |
| Hα NLR shift vs. Hβ NLR shift | 0.97 | <0.0001 | 16.40 ± 3.58        | 0.91 ± 0.02         |
| Hα ILR shift vs. Hβ ILR shift | 0.90 | <0.0001 | 1.86 ± 16.97        | 1.09 ± 0.05         |
| Hα VBLR shift vs. Hβ VBLR shift | 0.18 (0.41) | 0.041 (<0.0001) | -93.64 ± 45.30 | 0.06 ± 0.03 |
| L Hα NLR vs. L Hβ NLR | 0.93 | <0.0001 | 3.40 ± 1.29         | 0.93 ± 0.03         |
| L Hα ILR vs. L Hβ ILR | 0.96 | <0.0001 | 1.93 ± 1.08         | 0.97 ± 0.03         |
| L Hα VBLR vs. L Hβ VBLR | 0.96 | <0.0001 | 0.70 ± 1.03         | 0.99 ± 0.02         |

Notes. The values in brackets are for the sample without the 16 objects with highly redshifted Hβ VBLR components (>4000 km s⁻¹). The coefficient of correlation (r) is in the second column, the P-value which is a measure of significance of the correlation is given in the third column, and in the next columns are the coefficients A and B from the fit with a linear function: Hβ = A + B · Hα. The slopes are from regressions where X is taken as the independent variable.

3000 km s⁻¹ sub-sample (1) no correlation is observed between these properties.

The observed correlation between the G/S group ratio and Hβ FWHM may be caused by intrinsic reddening since reddening increases as objects get more edge-on (Gaskell et al. 2004) and the Hβ FWHM also increases (Wills & Browne 1986). However, this cannot explain the F/G and F/S correlation with Hβ FWHM, and also, a strong influence of reddening on the G/S ratio is not expected because of the close wavelengths of lines from those groups.

We also studied correlations between continuum luminosity (L_{α1500}) and Fe II group ratios, since these may indicate excitation processes in the emitting region. We found that the F/G and F/S ratios decrease in objects where the continuum level is higher. Observed correlations are stronger for the Hβ FWHM < 3000 km s⁻¹ sub-sample (F/G versus L_{α1500}: r = -0.51, P < 0.0001 and F/S versus L_{α1500}: r = -0.41, P < 0.0001). The ratio of G/S seems not to be dependent on continuum luminosity.

These correlations are the opposite of what would be expected from reddening, since reddening decreases with luminosity (Gaskell et al. 2004). There are a few effects that could destroy the expected reddening effect: (1) incorrect continuum subtraction; (2) host galaxy fraction which depends on the Eddington ratio; and (3) a different contribution of starlight in SDSS fiber which depends on the luminosity of the host galaxy and the redshift (see Gaskell & Kormendy 2009). There is a small possibility that these effects are important. As we already noted, the error bar in the continuum subtraction is smaller than 5%. Also, we examined whether the host galaxy contributions...
Figure 7. Fits of SDSS J141755.54 + 431155.8 in the 6400–6800 Å region. Hα is fitted with the sum of three Gaussians which represent emission from NLR, ILR, and VBLR and [N ii] λλ6548, 6583 lines are fitted with one Gaussian for each line of doublet. Narrow [N ii] lines are denoted with dashed lines.

Figure 8. Example of measuring EWs of the Fe ii group of lines. Top: fit spectrum (SDSS J020039.15−084554.9); middle: Fe ii lines and continuum; bottom: Fe ii lines normalized on the continuum level.

Figure 9. Example of measuring FWHM. Top: fitted broad Hβ (ILR+VBLR); bottom: FWHM is obtained as width on half maximum of the sum of ILR and VBLR Gaussians.

Table 4

| X         | Y         | r     | P          | A       | B       |
|-----------|-----------|-------|------------|---------|---------|
| EW Fe ii F | EW Fe ii S | 0.76  | <0.0001    | 0.21 ± 1.00 | 0.66 ± 0.03 |
| EW Fe ii F | EW Fe ii G | 0.80  | <0.0001    | −0.17 ± 1.29 | 0.96 ± 0.04 |
| EW Fe ii F | EW Fe ii G | 0.83  | <0.0001    | 5.39 ± 0.95  | 0.14 ± 0.04 |

Notes. Relationships are fitted with function \( Y = A + B \cdot X \). The coefficient of correlations, \( r \), the corresponding measure of the significance of correlations, \( P \), as well as the \( A \) and \( B \) coefficients, are shown in the table.

have influence on considered correlations. We found no correlations between the host galaxy fraction (determined in λ5100 Å) and Fe ii group ratios. The correlations appear instead to be connected with a weaker Baldwin effect for the F group (see Table 7).

We also investigated the correlation of the log(\( L_{H\alpha}/L_{H\beta} \)) with ratios of Fe ii groups. We found correlations with \( F/G \) (\( r = −0.36, P < 0.0001 \)) and with \( F/S \) ratio (\( r = −0.34, P < 0.0001 \)), but there is no correlation with \( G/S \) (Figure 13, Table 6), i.e., between the ratio of red and central parts. There is a possibility that these correlations are caused by intrinsic reddening.

3.2. Connection between Kinematical Properties of Fe ii Lines and Balmer Lines (Hα and Hβ)

We assume that the broadening of the lines arises by the Doppler effect caused by random velocities of emission clouds, and that the shifts of lines are a consequence of systemic motions of the emitting gas. We therefore studied the kinematical connection among emission regions by analyzing relationships between their widths and shifts obtained from our best fits.

The Doppler widths of Fe ii and Balmer lines (Hβ and Hα) are compared in Figure 14. On the X-axis we present Fe ii width and on the Y-axis the widths of the Hβ (first panel) and Hα (second panel) components. The widths of the NLR
components are denoted by triangles, the ILR components with circles, and the VBLR components with squares. Dotted lines show the average values of the widths: vertical lines for Fe\textsc{ii} components and horizontal lines for H$\beta$ (or H$\alpha$). For the sample of 302 AGNs (first panel), the average value of Fe\textsc{ii} width and dispersion of the sample is $1430 \pm 440$ km s$^{-1}$, while the average...
values for Hβ components are 300 ± 150 km s\(^{-1}\) (NLR), 1570 ± 700 km s\(^{-1}\) (ILR), and 4360 ± 1440 km s\(^{-1}\) (VBLR). For the selected sample of 133 AGNs that have the H\(\alpha\) line in the spectra (second panel), the averaged value of the Fe\(\pi\) width is 1310 ± 410 km s\(^{-1}\) and for the Hα components: 240 ± 90 km s\(^{-1}\) (NLR), 1160 ± 560 km s\(^{-1}\) (ILR), and 4060 ± 1650 km s\(^{-1}\) (VBLR). It is obvious that the averaged Fe\(\pi\) width (~1400 km s\(^{-1}\)) is very close to the average widths of the ILR Hβ and Hα components (1568 km s\(^{-1}\) and 1156 km s\(^{-1}\), respectively), while the averaged widths of NLR and VBLR components are significantly different from the Fe\(\pi\) width.

Relationships among the widths of the Fe\(\pi\) and ILR components are also presented in Figure 15 (Table 7). The correlation between the Fe\(\pi\) width and the width of Hα ILR is \(r = 0.77, P < 0.0001\), and between the Fe\(\pi\) width and the Hβ ILR width it is \(r = 0.73, P < 0.0001\). We also found a correlation between the widths of the Fe\(\pi\) and the VBLR (\(r = 0.66, P < 0.0001\) for the Hα VBLR, and \(r = 0.45, P < 0.0001\) for Hβ VBLR).

Relationships between the shifts of Fe\(\pi\) and Hα and Hβ components were also considered (Table 7). We found correlations with the shifts of Hα ILR (\(r = 0.50, P = 0.0004\)) and the Hβ ILR component (\(r = 0.39, P < 0.0001\)), but no correlation between the shift of Fe\(\pi\) and the shifts of other Hα and Hβ components.

We found that Fe\(\pi\) lines tend to have an averaged redshift of 270 ± 180 km s\(^{-1}\) with respect to the transition wavelength, and with respect to narrow lines 100 ± 240 km s\(^{-1}\) (see Figure 16).

### 3.3. Correlations between the Fe\(\pi\) Line Groups and Other Emission Lines

Correlations between the luminosity of the Fe\(\pi\) multiplet groups, total Fe\(\pi\), and luminosities of the [N\(\pi\)] and [O\(\pi\)] lines are presented in Table 8. In the L [N\(\pi\)] versus L Fe\(\pi\) plot, seven outliers are observed with negligible [N\(\pi\)]. They are probably caused by an underestimate in the fit of the [N\(\pi\)] lines due to the blending with the Hα line. Without those outliers, the correlation is \(r = 0.70, P < 0.0001\). There is no correlation between L [N\(\pi\)] and L [O\(\pi\)] and L Fe\(\pi\).

We analyzed relationships among the luminosities of the Fe\(\pi\) line groups and the NLR, ILR, and VBLR Hα components (Table 8). All three Hα components are correlated with the Fe\(\pi\) line groups. Correlations are stronger with the ILR and VBLR components than with the NLR components. The same analysis was carried out for the luminosities of Fe\(\pi\) line groups and the NLR, ILR, and VBLR components of Hβ (Table 8). The NLR component of Hβ also has a weaker correlation with Fe\(\pi\) lines (\(r \sim 0.60, P < 0.0001\)) than broad Hβ components (\(r \sim 0.90, P < 0.0001\)).

We also investigated the anti-correlations between EW Fe\(\pi\) and EW [O\(\pi\)], and between EW Fe\(\pi\) and EW [O\(\pi\)]/EW Hβ (Boroson & Green 1992). We confirmed the existence of these relationships in our sample, with Fe\(\pi\) lines separated into F, S, and G line groups (Figure 17, Table 9). A difference from Boroson & Green (1992), who measured the EWS of all lines referring to the continuum level at the \(\lambda 4861\), is that we calculated the EWS by estimating the continuum below all the Fe\(\pi\) lines considered (see Figure 8). Note also that Boroson
Figure 14. Widths of the Fe ii lines compared with the widths of the Hβ (left) and Hα (right) components. On the X-axis are the widths of Fe ii, and on Y-axis are the widths of the NLR (triangles), ILR (circles), and VBLR (squares) components of Hβ (Hα). The dotted vertical line shows the average value of Fe ii widths, while the dotted horizontal lines show the average values of the Hβ (Hα) components. The average value of the Fe ii lines is the same as or very close to the average width value of the ILR components of Hβ and Hα.

Figure 15. Correlation between the widths of Fe ii and the Hβ ILR (left), Hα ILR (middle), and Hα VBLR components (right). In all cases, correlations are observed ($r = 0.67, 0.72, 0.62$), indicating kinematical connection between these emission regions.

Table 7

| Relationship      | $w_{H\alpha}$ NLR | $w_{H\alpha}$ ILR | $w_{H\alpha}$ VBLR | $w_{H\beta}$ NLR | $w_{H\beta}$ ILR | $w_{H\beta}$ VBLR |
|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| $r$               | 0.01              | 0.77              | 0.66              | 0.05              | 0.73              | 0.45              |
| $P$               | <0.0001           | <0.0001           | <0.0001           | <0.0001           | <0.0001           | <0.0001           |
| $A$               | 232.71 ± 27.12    | 49.65 ± 11.36     | 609.64 ± 356.76  | 275.84 ± 30.17   | 114.23 ± 94.28   | 2241.03 ± 251.81  |
| $B$               | 0.00 ± 0.02       | 0.96 ± 0.08       | 2.63 ± 0.26       | 0.02 ± 0.02       | 1.17 ± 0.06       | 1.48 ± 0.17       |
| $r$               | 0.02              | 0.30              | 0.01              | 0.00              | 0.39              | −0.17             |
| $P$               | 0.84              | 0.0004            | 0.930             | 0.928             | <0.0001           | 0.003             |
| $A$               | 149.78 ± 8.88     | 66.10 ± 26.11     | −49.14 ± 44.47   | 165.22 ± 9.63    | 55.32 ± 14.80    | 1301.87 ± 96.29   |
| $B$               | 0.00 ± 0.02       | 0.26 ± 0.07       | 0.01 ± 0.12       | 0.00 ± 0.03       | 0.32 ± 0.04       | −0.83 ± 0.28      |
| $P$               | <0.0001           | <0.0001           | <0.0001           | <0.0001           | <0.0001           | <0.0001           |
| $A$               | 2241.03 ± 251.81  | 1301.87 ± 96.29   | 1301.87 ± 96.29   | 1301.87 ± 96.29   | 1301.87 ± 96.29   | 1301.87 ± 96.29   |
| $B$               | 1.48 ± 0.17       | −0.83 ± 0.28      | −0.83 ± 0.28      | −0.83 ± 0.28      | −0.83 ± 0.28      | −0.83 ± 0.28      |

Notes. Relationships are fitted with function $Y = A + B \cdot X$. The coefficient of correlations, $r$, the corresponding measure of the significance of correlations, $P$, as well as the $A$ and $B$ coefficients, are shown in the table.
Table 8
Correlations Between Luminosities (L) of the Fe II Lines (Total Fe II, F, S, and G Line Groups) and Luminosities of [N II], [O III], and Hα and Hβ Components

|                      | log(L [N II]) | log(LF) | log(LS) | log(LG) | log(L I Zw 1 Group) |
|----------------------|--------------|---------|---------|---------|--------------------|
| log(L [N II])        | r            | -0.73   | 0.72    | 0.67    | 0.72               |
|                      | P            | <0.0001 | <0.0001 | <0.0001 | <0.0001            |
| log(L [N II]/L [O III]) | r          | 0.06    | 0.08    | 0.08    | 0.10               |
|                      | P            | <0.0001 | <0.0001 | <0.0001 | 0.02               |
| log(L Hα NLR)        | r            | 0.76    | 0.74    | 0.71    | 0.75               |
|                      | P            | <0.0001 | <0.0001 | <0.0001 | <0.0001            |
| log(L Hα ILR)        | r            | 0.91    | 0.90    | 0.84    | 0.89               |
|                      | P            | <0.0001 | <0.0001 | <0.0001 | <0.0001            |
| log(L Hα VBLR)       | r            | 0.90    | 0.89    | 0.82    | 0.87               |
|                      | P            | <0.0001 | <0.0001 | <0.0001 | <0.0001            |
| log(L Hβ NLR)        | r            | 0.64    | 0.63    | 0.61    | 0.63               |
|                      | P            | <0.0001 | <0.0001 | <0.0001 | <0.0001            |
| log(L Hβ ILR)        | r            | 0.93    | 0.93    | 0.88    | 0.92               |
|                      | P            | <0.0001 | <0.0001 | <0.0001 | <0.0001            |
| log(L Hβ VBLR)       | r            | 0.95    | 0.95    | 0.90    | 0.93               |
|                      | P            | <0.0001 | <0.0001 | <0.0001 | <0.0001            |

Notes. Relationships are fitted with the function Y = A + B \cdot X. The coefficient of correlations, r, and the corresponding measure of the significance of correlations, P, are shown in the table.

Table 9
The Same as in Table 8, but for EWs

|                      | EW Fe II Total | EW F | EW S | EW G | EW I Zw 1 Group |
|----------------------|----------------|------|------|------|-----------------|
| EW [N II]            | r              | -0.27| -0.20| -0.22| -0.27           |
|                      | P              | 0.002| 0.02 | 0.01 | 0.001           |
| EW [O III]           | r              | -0.39| -0.40| -0.37| -0.42           |
|                      | P              | <0.0001| <0.0001| <0.0001| <0.0001         |
| EW [O III]/EW Hβ     | r              | -0.46| -0.47| -0.43| -0.45           |
|                      | P              | <0.0001| <0.0001| <0.0001| <0.0001         |
| EW Hα NLR            | r              | -0.18| -0.18| -0.18| 0.19            |
|                      | P              | 0.04 | 0.04 | 0.04 | 0.02            |
| EW Hα ILR            | r              | -0.23| -0.17| -0.18| -0.29           |
|                      | P              | 0.007| 0.04 | 0.04 | 7E-4            |
| EW Hα VBLR           | r              | -0.28| -0.23| -0.28| -0.34           |
|                      | P              | 0.001| 0.007| 1E-4 | <0.0001         |
| EW Hβ NLR            | r              | 0.01 | 0.01 | -0.09| -0.04           |
|                      | P              | 0.90 | 0.91 | 0.11 | 0.46            |
| EW Hβ ILR            | r              | -0.02| 0.02 | 0.07 | -0.07           |
|                      | P              | 0.70 | 0.69 | 0.25 | 0.24            |
| EW Hβ VBLR           | r              | 0.12 | 0.11 | 0.11 | 0.04            |
|                      | P              | 0.03 | 0.07 | 0.07 | 0.52            |

The correlations between EW Fe II and the Doppler widths of Hβ components are also considered (Table 10). As was expected, an inverse correlation was found between EW Fe II and the widths of the broad Hβ components (ILR and VBLR, as well as for the Hβ FWHM, r ∼ −0.30, P < 0.0001). These correlations are part of EV1. But, contrary to this, we found a positive correlation (r = 0.30, P < 0.0001) between the EW Fe II and the width of NLR component.

3.4. Relations Among Emission-line Strength and Continuum Luminosity

In Section 3.3, we have confirmed the anti-correlation EW Fe II versus EW [O III] (also EW Fe II versus EW [O III]/EW Hβ). To try to understand the underlying physics which governs this anti-correlation, we examined its dependence of the continuum luminosity and redshift.

& Green (1992) used mainly measurements from lines from multiplets 37 and 38.

We found a correlation between total EW Fe II and EW [O III]: r = −0.39, P < 0.0001. The correlation coefficient was significantly lower for the lines obtained from I Zw 1 (r = −0.20, P = 0.0006) than for the other three groups (see Table 9). We also analyzed relationships between EW Fe II line groups and EW [O III]/EW Hβ. For total EW Fe II, we found r = −0.46, P < 0.0001 (Figure 17, right), but for lines from I Zw 1 group we found r = −0.28, P < 0.0001.

No significant correlations were found between EW Fe II and EW [N II] lines (Table 9).

We also investigated whether there were any trends between EWs of Fe II F, S, G line groups and EWs of NLR, ILR, and VBLR Hα and Hβ components (Table 9). We found no significant correlations, besides a small correlation detected for EW Hα VBLR versus EW Fe II G.
Because of selection effects, cosmological redshift, $z$, and continuum luminosity are highly correlated in our sample, so it is difficult to clearly distinguish which influence dominates in some correlations. Since our sample has a more uniform redshift distribution than continuum luminosity distribution (see Figure 2), we binned EWs of the [O\textsc{iii}] and Fe\textsc{ii} lines within the $z = 0$–0.7 range, using a $\Delta z = 0.1$ bin size. The binned data are presented in Figure 18. It can be seen that as redshift increases in the $z < 0.4$ range, EW Fe\textsc{ii} also increases, but EW [O\textsc{iii}] decreases (Figure 18). For $z > 0.4$, the trend is not so obvious, probably due to the larger scatter of the data at higher redshifts.

We derived correlation coefficients for the ratios of the [O\textsc{iii}], Fe\textsc{ii}, and H\beta lines and $L_{\lambda 5100}$ (also with redshift, see Figure 19, Table 11). A significant anti-correlation was found for the ratio of EW [O\textsc{iii}]/EW Fe\textsc{ii} versus $L_{\lambda 5100}$ and for EW [O\textsc{iii}]/EW Fe\textsc{ii} versus $z$. We found that the ratios of EW [O\textsc{iii}]/EW H\beta and EW H\beta NLR/ EW Fe\textsc{ii} also decrease as $L_{\lambda 5100}$ (redshift) increases. As in the previous case, the difference between the $P$-values for correlation with $L_{\lambda 5100}$ and with $z$ is very small, so we cannot tell which effect dominates. In contrast to this, for EW H\beta total/ EW Fe\textsc{ii} versus $L_{\lambda 5100}$, no significant trend is

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**Figure 16.** Distribution of the Fe\textsc{ii} shift with respect to the transition wavelength (left) and distribution of the Fe\textsc{ii} shift with respect to the [O\textsc{iii}] lines (right).

**Figure 17.** Relationship between the EW [O\textsc{iii}] $\lambda 5007$ vs. EW Fe\textsc{ii} (left) and EW [O\textsc{iii}]/EW H\beta vs. EW Fe\textsc{ii} (right).

**Figure 18.** Relationship between the EWs, EW [O\textsc{iii}] $\lambda 5007$, and EW Fe\textsc{ii}, binned for cosmological redshift. The error bars are the dispersions in each sub-sample within different redshift bins.

**Table 10**

|        | EW Fe\textsc{ii} |
|--------|------------------|
| Width H\beta NLR | $r$ | 0.30 |
|        | $P$ | <0.0001 |
| Width H\beta ILR | $r$ | −0.31 |
|        | $P$ | <0.0001 |
| Width H\beta VBLR | $r$ | −0.34 |
|        | $P$ | <0.0001 |
| H\beta FWHM | $r$ | −0.30 |
|        | $P$ | <0.0001 |

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Because of selection effects, cosmological redshift, $z$, and continuum luminosity are highly correlated in our sample, so it is difficult to clearly distinguish which influence dominates in some correlations. Since our sample has a more uniform redshift distribution than continuum luminosity distribution (see Figure 2), we binned EWs of the [O\textsc{iii}] and Fe\textsc{ii} lines within the $z = 0$–0.7 range, using a $\Delta z = 0.1$ bin size. The binned data are presented in Figure 18. It can be seen that as redshift increases in the $z < 0.4$ range, EW Fe\textsc{ii} also increases, but EW [O\textsc{iii}] decreases (Figure 18). For $z > 0.4$, the trend is not so obvious, probably due to the larger scatter of the data at higher redshifts.

We derived correlation coefficients for the ratios of the [O\textsc{iii}], Fe\textsc{ii}, and H\beta lines and $L_{\lambda 5100}$ (also with redshift, see Figure 19, Table 11). A significant anti-correlation was found for the ratio of EW [O\textsc{iii}]/EW Fe\textsc{ii} versus $L_{\lambda 5100}$ and for EW [O\textsc{iii}]/EW Fe\textsc{ii} versus $z$. We found that the ratios of EW [O\textsc{iii}]/EW H\beta and EW H\beta NLR/ EW Fe\textsc{ii} also decrease as $L_{\lambda 5100}$ (redshift) increases. As in the previous case, the difference between the $P$-values for correlation with $L_{\lambda 5100}$ and with $z$ is very small, so we cannot tell which effect dominates. In contrast to this, for EW H\beta total/ EW Fe\textsc{ii} versus $L_{\lambda 5100}$, no significant trend is
observed, but for EW Hβ/EW Fe ii versus z, there is a weak correlation \( r = 0.28, P = 1.3E-6 \).

Because of discrepancies in the properties observed between sub-samples within different Hβ FWHM ranges (see Section 3.1), we analyzed the relationships separately for the sub-samples with FWHM Hβ < 3000 km s\(^{-1}\) and FWHM Hβ > 3000 km s\(^{-1}\). It will be noticed that, in general, all the correlations considered are stronger for the FWHM Hβ > 3000 km s\(^{-1}\) sub-sample than for spectra with narrower Hβ lines (see Table 11). The only exception is the correlation of EW Hβ NLR/EW Fe ii versus \( L_{\lambda 5100} \), which is more significant for the FWHM Hβ < 3000 km s\(^{-1}\) sub-sample.

Table 11

| Correlation | log \( L_{\lambda 5100} \) | log z | (1) log \( L_{\lambda 5100} \) | (2) log \( L_{\lambda 5100} \) | log \( r \) | log \( P \) |
|-------------|-----------------|------|-----------------|-----------------|--------|--------|
| log (EW [O iii]/EW Fe ii) | -0.46 | -0.48 | -0.44 | -0.45 | -0.55 | 5.67E-9 |
| log(EW[O iii]/EW Hβ) | -0.49 | -0.48 | -0.43 | -0.43 | -0.50 | 1.89E-9 |
| log(EWHβ total/EW Fe ii) | -0.19 | -0.28 | -0.28 | -0.31 | -0.45 | 1.66E-8 |
| log(EWHβ NLR/EW Fe ii) | -0.42 | -0.42 | -0.52 | -0.51 | -0.31 | 4.00E-4 |

Note. The correlations with \( P < 0.0001 \) are given in bold print.

It is interesting to connect these anti correlations (EW Fe ii versus EW [O iii] and considered ratios versus \( L_{\lambda 5100} \)) with the Baldwin effect. Baskin & Laor (2004) confirmed a correlation between the Baldwin effect and some of the emission parameters which define EV1 correlations (which are related to EW [O iii]–EW Fe ii anti-correlation). Also, it has been found that the [O iii] lines show a strong Baldwin effect (Dietrich et al. 2002). On the other hand, no Baldwin effect has been noticed
for the optical Fe\textsc{ii} and H\textbeta\ lines (Dietrich et al. 2002), or even an inverse Baldwin Effect has been reported: Croom et al. (2002) found an inverse Baldwin effect in H\beta and Netzer & Trakhtenbrot (2007) found one for both H\beta and optical Fe\textsc{ii} lines.

Because of this, we examined the dependence of the EWs of Fe\textsc{ii}, H\beta and [O\textsc{iii}] lines versus $L_{5100}$ and $z$ in our sample. Since H\beta is decomposed in NLR, ILR, and VBLR and the iron lines are separated in the groups, they can be considered in more detail. Also, we performed separate analyses for the sub-samples with different H\beta FWHM ranges (Table 11).

Analyzing the total sample (i.e., the whole H\beta FWHM range), it is obvious that Fe\textsc{ii} lines show an inverse Baldwin effect, which is especially strong for the central (r = 0.33, $P < 0.0001$) and red part (r = 0.44, $P < 0.0001$) of the Fe\textsc{ii} shelf (S and G groups), as well as for the group of lines from I Zw 1 (r = 0.32, $P < 0.0001$). The correlation of total Fe\textsc{ii} versus $L_{5100}$ is presented in Figure 20. What is interesting is that a strong inverse Baldwin effect is not observed for the F lines (blue part; r = 0.16, $P = 0.004$). In the relationship between H\beta components and continuum luminosity for the total sample, no trend is observed for broad H\beta (ILR and VBLR), but it can be noticed that the narrow H\beta component anti-correlates with continuum luminosity (r = −0.36, $P < 0.0001$),—i.e., they show a Baldwin effect—as well as the [O\textsc{iii}] lines, for which the previously found trend is confirmed (r = −0.43, $P < 0.0001$ — see Figure 20).

If we compare these correlations with the corresponding correlations with redshift, it is obvious that the iron lines (total Fe\textsc{ii} and the multiplet groups) correlate more strongly with redshift than with luminosity. In the case of other lines we consider, the difference between the correlations with $L_{5100}$ and $z$, is not so significant. Generally, it seems that the lines which show an inverse Baldwin effect (Fe\textsc{ii} and H\beta VBLR) correlate more significantly with redshift than with luminosity, while the lines which show a (normal) Baldwin effect ([O\textsc{iii}] and H\beta NLR) have more significant correlations with continuum luminosity.

We find that the coefficients of correlations between the EWs of lines and the continuum luminosity (and $z$) depend on the H\beta FWHM range of the sub-sample. It seems that continuum luminosity affects iron lines and H\beta more for the sub-sample with narrower H\beta line (FWHM H\beta $< 3000$ km s$^{-1}$). In that sub-sample, all Fe\textsc{ii} groups show a stronger inverse Baldwin effect, H\beta NLR decreases more strongly with an increase in continuum luminosity, and an inverse Baldwin effect is also observed for H\beta VBLR (r = 0.41, $P < 0.0001$). This is not seen in the FWHM H\beta $> 3000$ km s$^{-1}$ sub-sample. In contrast with this the Baldwin effect is stronger in the [O\textsc{iii}] lines for the FWHM H\beta $> 3000$ km s$^{-1}$ sub-sample.

4. DISCUSSION

From our analysis of optical Fe\textsc{ii} lines ($\lambda\lambda 4400$–5400), we can try to investigate physical and kinematical characteristics of the Fe\textsc{ii} emitting region in AGN as well as the connection between the Fe\textsc{ii} and other emission regions. We have investigated above correlations between the Fe\textsc{ii} emission properties and some spectral features. Correlations of the Fe\textsc{ii} lines were considered separately for different multiplet groups, which enable more detailed analysis. Here we give some discussion of the results we have obtained.

4.1. The Fe\textsc{ii} Line Group Ratios—Possible Physical Conditions in the Fe\textsc{ii} Emitting Region

Although we used very simple approximations to calculate the intensities of the observed Fe\textsc{ii} lines, we found that the calculated intensities can satisfactorily fit the Fe\textsc{ii} shelf within the 4400–5500 Å range. This approach is very simplified, but in some cases, it enables a better fit than much more complicated theoretical models (see Appendix B). We included excitation temperature in our calculation and found that it is in the most cases around 10,000 K ($9646 \pm 2143$ K); see Figure 4. Roughly the estimated temperature of the Fe\textsc{ii} emitting region from our fitting (assumed template) is in a good agreement with the prediction given earlier in literature ($\sim 7000$ K; Joly 1987).

We found that the most intensive emission in the optical part arises in transitions with the lower term b$^4$F (multiplets 37 and 38). We also considered the ratios of multiplet groups. The line ratios may indicate some physical properties. For example, it has been shown that the Balmer line ratios are velocity dependent in AGNs (see, e.g., Shuder 1982, 1984; Crenshaw 1986; Stirpe 1990, 1991; Snedden & Gaskell 2007) and this is probably related to a range of physical conditions (electron temperature and density) and to the radiative transfer effects (see, e.g., Popović 2003, 2006). In general, the ratios between the F, G, and S groups indicate the ratio between the blue, red, and central parts of the Fe\textsc{ii} shelf around H\beta lines. As can be seen in Table 5, there is correlation between the F/G, F/S, and G/S ratios versus FWHM of H\beta line. It is interesting that this correlation...
is not present when we consider the cases where FWHM(Hβ) < 3000 km s^{-1}. We should note here that for the case FWHM(Hβ) < 3000 km s^{-1} we had only ΔFWHM(Hβ) ≈ 2000 km s^{-1} and this may affect the obtained results. As we mentioned above, the separation of the sample into two sub-samples according to the Hβ FWHM is similar as given in Sulentic et al. (2009, and reference therein). It seems that the characteristics of the Pop A (FWHM Hβ < 4000 km s^{-1}) and B (FWHM Hβ > 4000 km s^{-1}) of AGNs (as proposed by the above-mentioned authors) can be recognized in the Fe II line ratios: namely, the correlations and trends observed in Table 5 indicate that the ratios of blue and red (as well as blue and central) parts of Fe II shelf anti-correlate with continuum luminosity more strongly in Pop A than in Pop B. Also, for Pop B, all considered flux ratios (F/G, F/S, and G/S) increase with increasing Hβ width and with decreasing Fe II shift, while that trend is not observed in Pop A.

The observed anti-correlations of the F/G and F/S ratios versus L_{5100} could be affected by the differing degrees of the inverse Baldwin effect observed for the Fe II lines from the three line groups since the EWs of the S and G groups increase more significantly with L_{5100} (r = 0.33 and r = 0.43, P < 0.0001, respectively) than those of the F group (r = 0.16, P = 0.04, see Table 11). Note here that the ratio of G/S does not correlate with the continuum. Also, since the inverse Baldwin effect for the S and G groups is stronger for the FWHM Hβ < 3000 km s^{-1} sub-sample, the correlations of F/G and F/S versus L_{5100} are stronger for FWHM Hβ < 3000 km s^{-1} (Table 5).

From the above-mentioned correlations, we can ask some intriguing questions about the physical conditions and processes in the Fe II emitting region: (1) Which processes cause the increase of Fe II EW with increasing L_{5100}? Note that the EWs of the majority of the other emission lines in AGN spectra decrease with increasing L_{5100} (see Dietrich et al. 2002); (2) Why is the inverse Baldwin effect correlation lower for the F group compared with the S and G groups?; and (3) What causes that inverse Baldwin effect for Fe II (in S and G) to be more significant in the sub-sample with FWHM Hβ < 3000 km s^{-1} than in one with a broader Hβ line? Answering some of these questions may lead to a better understanding of the complex Fe II emitting region.

4.2. Location of the Fe II Emitting Region

Marziani & Sulentic (1993) and Popović et al. (2004) noted earlier that Fe II lines may originate in the ILR, which may be the transition from the torus to the BLR. Recently, other authors also found that the optical Fe II emission may arise from a region in the outer parts of the BLR or several times larger than the Hβ one (Hu et al. 2008b; Kuehn et al. 2008; Popović et al. 2004, 2007, 2009; Gaskell et al. 2007).

To explore the kinematics of the Fe II emitting region, which may indicate the location of the Fe II emission, we compared the derived widths and shifts of the Fe II and the Hβ and Hα components. As can be seen in Figures 14 and 15, there is an indication that Fe II emitting region is located as the IL-emitting region. Moreover, the correlation between the Doppler widths of the Fe II and IL regions is significantly higher than for the VBLR and NLR. There is no significant correlation between the Doppler widths of the Fe II and NL regions (r = 0.01, P = 0.87 for Hα, r = 0.05, P = 0.40 for Hβ), but there is a correlation between the Fe II and VBLR regions (r = 0.66, P < 0.0001 for Hα, r = 0.45, P < 0.0001 for Hβ). This may indicate that one more component of the Fe II lines is arising from the VBLR. Note here that, due to the complex Fe II template, we assumed only one component for each Fe II line (see Section 2.2). The reasonable fits of the Fe II shelf indicate that the VBLR component of Fe II should be significantly weaker than the ILR one.

These indications are also supported by the correlation between the shift of the Fe II lines and the ILR components of Hα and Hβ. The distribution of the Fe II line shifts is shown in Figure 16. The shift is obtained with respect to the transition wavelength (Figure 16, left) and with respect to the narrow lines (Figure 16, right). We found that Fe II lines are slightly redshifted, which is in agreement with the results of Hu et al. (2008b). But in this case, the average value of the Fe II shift relative to the transition wavelength is 270 ± 180 km s^{-1}, while the average value of the Fe II shift with respect to the narrow lines is 100 ± 240 km s^{-1}. This implies a significantly smaller redshift than that found in Hu et al. (2008b). A slightly redshifted Fe II emission may indicate that Fe II lines arise in an inflowing region (see Gaskell 2009).

4.3. EW Fe II versus EW [O III] Anti-correlation

One of the problems mentioned in Section 1 is the anti-correlation between the EWs of the [O III] and Fe II lines which is related to EV1 in the analysis of Boroson & Green (1992). Some physical causes proposed to explain EV1 correlations are (1) Eddington ratio L/L_Edd (Boroson & Green 1992; Baskin & Laor 2004), (2) black hole mass M_BH, and (3) inclination angle (Miley & Miller 1979; Wills & Browne 1986; Marziani et al. 2001). Wang et al. (2006) also suggested that EV1 may be related to AGN evolution.

To try to understand the EW Fe II versus EW [O III] anti-correlation, we examined its relationship to continuum luminosity and redshift (see Section 3.4, Table 11). We found an anti-correlation between the EW [O III] and EW Fe II, and L_{5100}. Also, we examined the relations of EWs of Fe II and [O III] lines versus L_{5100}. We confirmed a strong Baldwin effect for [O III] lines, and an inverse Baldwin effect for EW Fe II lines, i.e., we found that as continuum luminosity increases, EW Fe II also increases, but EW [O III] decreases. This implies that the EW Fe II−EW [O III] anti-correlation may be influenced by a Baldwin effect for [O III] and an inverse Baldwin effect for Fe II lines. Also, in our analysis we found that the strength of the Baldwin effect depends on the Hβ FWHM of the sample (see Table 11). Note that Hβ FWHM is one of the parameters in EV1. As it is mentioned in Section 1, some indications of the connection between the Baldwin effect and EV1 have been given in Baskin & Laor (2004) and Dong et al. (2009). Ludwig et al. (2009) found that the significance of the EV1 relationships is a strong function of continuum luminosity, i.e., the relationships between EW Fe II, EW [O III], and Hβ FWHM can be detected only in a high-luminosity sample of AGNs (logL_{5100} > 44.7), as well as a Baldwin effect for [O III] lines.10

The origin of the Baldwin effect is still not understood and is a matter of debate. The increase of the continuum luminosity may cause a decrease of the covering factor, or changes in the spectral energy distribution (softening of the ionizing continuum) which may result in the decrease of EWs. The inclination angle may also be related to Baldwin effect (for review see Green et al. 2001). The physical properties which are usually considered to be a primary cause of the Baldwin effect are M_BH (Warner et al.

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10 The majority of objects in our sample have continuum luminosities in the range 44.5 < logL_{5100} < 46 range (see Figure 2).
We investigated whether the correlations observed between $L_{\lambda 5100}$ and the EWs of the lines (as well as EW [O III] versus EW Fe II) are primarily caused by evolution. Since continuum luminosity is strongly correlated with cosmological redshift in our sample, it is difficult to separate luminosity from evolutionary effects. The exceptions are correlations of EW Fe II versus $z$, as well as the ratio $EW$ $\beta$ $/$ $EW$ Fe II versus $z$, which are significantly stronger than correlations of the same quantities with $L_{\lambda 5100}$. This implies that the inverse Baldwin effect of Fe II may be governed first of all by an evolutionary effect. This result is in agreement with results of Green et al. (2001).

5. CONCLUSIONS

In this paper, we have investigated the characteristic of the Fe II emission region, using the sample of 302 AGNs from SDSS. To analyze the Fe II emission, an Fe II template was constructed by grouping the strongest Fe II multiplets into three groups, according to the atomic properties of transitions.

We have investigated the correlations of these Fe II groups and their ratios with other lines in spectra. In this way, we tried to find some physical connection between the Fe II and other emitting regions, as well as to connect Fe II atomic structure with the physical properties of the emitting plasma.

We also investigated the kinematical connection between Fe II and the Balmer emission region. In particular, the anti-correlation of EW Fe II–EW [O III] and its possible connection with AGN luminosity and evolution were analyzed. From our investigation we can outline the following conclusions.

1. We have proposed here an optical Fe II template for the 4400–5500 Å range, which consists of three groups of Fe II multiplets, grouped according to the lower terms of transitions ($F$, $S$, and $G$), and an additional group of lines reconstructed from the I Zw 1 spectrum. We found that the template can satisfactorily fit the Fe II lines. In spectra in which Fe II emission lines have different relative intensities than in I Zw 1, this template fits better than empirical and theoretical templates based on the I Zw 1 spectrum (see more in Appendix B). Using this template, we are able to consider different groups of transitions which contribute to the blue, central, and red parts of Fe II shelf around the $\beta$+[O III] lines.

2. We find that the ratios of different parts of the iron shelf ($F/G$, $F/S$, and $G/S$) depend on some spectral properties such as continuum luminosity, $\beta$ FWHM, the shift of Fe II, and the Hα/$\beta$ flux ratio. Also, it is noticed that spectra with $\beta$ FWHM greater and less than $\sim 3000$ km s$^{-1}$ have different properties, which is reflected in significantly different coefficients of correlation between the parameters.

3. We found that the Fe II emission is mainly characterized with a random velocity of $\sim 1400$ km s$^{-1}$ that corresponds to the ILR origin, which is also supported by the significant correlation between the width of Fe II and Hα, $\beta$ ILR widths. This is in agreement with the previous investigations (Popović et al. 2004; Hu et al. 2008b; Kuehn et al. 2008), but unlike the earlier investigations, we found a slight correlation with the width of VBLR. Therefore, it is possible that Fe II is partly produced in the VBLR and cannot be resolved from continuum luminosity. Also, we found that the Fe II lines are slightly redshifted relative to the narrow lines ($\sim 100$ km s$^{-1}$; see Figure 16).

4. The Balmer lines were decomposed into NLR, ILR, and VBLR components and relationships among H$\beta$ components and some spectral properties were investigated. We found a positive correlation between the width of narrow lines and EW Fe II ($r = 0.30$, $P < 0.0001$), while the width of the broad H$\beta$ components anti-correlates with EW Fe II. Also, we found a Baldwin effect in the case of the H$\beta$ NLR component, while the ILR component showed no correlation with continuum luminosity, and the VBLR component shows an inverse Baldwin effect for the FWHM < 3000 km s$^{-1}$ sub-sample.

5. We confirm in our sample the anti-correlation between EW Fe II and EW [O III], which is related to EV1 in Boroson & Green (1992), and we examined its dependence on the continuum luminosity and redshift. We found an inverse Baldwin effect for Fe II lines from the central and red parts of the Fe II shelf ($S$ and $G$), but for Fe II lines from blue part ($F$), no correlation was observed. A Baldwin effect was confirmed for the [O III] lines. Since EW Fe II increases, and EW [O III] decreases with increases of continuum luminosity (and also the trend of decreasing of the EW [O III]/EW Fe II ratio with luminosity is obvious), the observed EW Fe II versus EW [O III] anticorrelation is probably due to the same physical reason that causes the Baldwin effect. Moreover, it is observed that the coefficients of correlation due to Baldwin effect depend on the $\beta$ FWHM range of a sub-sample, which also implies the connection between the Baldwin effect and EV1. A decreasing trend is observed for EW [O III]/EW H$\beta$ versus continuum luminosity.

6. We found that the EW of the Fe II lines and the EW $\beta$ FWHM/EW Fe II ratio have a stronger correlation with redshift than with continuum luminosity. This implies that the inverse Baldwin effect of Fe II may be primarily caused by evolution.

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APPENDIX A

THE SAMPLE SELECTION

Using an SQL search with the requirements mentioned in Section 2.1, we obtained 497 AGN spectra with broad emission lines. From that number, 188 spectra were rejected because of noise in the iron emission line region. An example of the rejected spectrum is shown in Figure 21. Also, three spectra were rejected because of bad pixels, and one because of very strong double-peak emission in Hβ (SDSS J154213.91+183500.0).

Three more spectra with broad Hβ and practically without the Fe II emission were rejected since it was not possible to fit the Fe II lines (SDSS J132756.15+111443.6, SDSS J104326.47+110524.2, and SDSS J083343.47+074654.5). These three spectra are shown in Figure 22. There is also a possibility that in these three objects the Fe II lines are very broad and weak so that they cannot be distinguished from the continuum emission.

The sample contains 302 AGN spectra (tables with the SDSS identification and obtained parameters from the best fit are available electronically only in Table 12). To test the host galaxy contribution in the selected sample of 302 AGNs, we have compared our sample with the set of AGNs for which the host galaxy fraction is determined in Vanden Berk et al. (2006). We found 106 common objects. In the case of 48 AGNs (45% of the sample), there is practically no host galaxy contribution (0%), and in the rest of the objects, the contribution of the host galaxy is mainly smaller than 20%.

APPENDIX B

COMPARISON WITH OTHER Fe II TEMPLATES

We compared two Fe II templates (one empirical and one theoretical) with our template. The empirical Fe II template was taken from Dong et al. (2008) using 46 broad and 95 narrow lines identified by Veron-Cetty et al. (2004) in the I Zw 1 spectrum within a 4400–5500 Å range. The Fe II lines were fitted with six free parameters (the width, shift, and intensity for narrow lines and the width, shift and intensity for broad lines). We also considered the theoretical model from Bruhweiler & Verner (2008) calculated for \( \log\left[ n_{\text{H}} / (\text{cm}^{-3}) \right] = 11 \), \( [\xi] / (1 \text{ km s}^{-1}) = 20 \), and \( \log\left[ \Phi_{\text{H}} / (\text{cm}^{-2} \text{s}^{-1}) \right] = 21 \), since we found that this gave the best fit for those values of physical parameters. With this model, Fe II lines were fitted with three free parameters (width, shift, and intensity).

Figure 23 shows the spectrum of SDSS J020039.15−084554.9, an object in which the iron lines have relative intensities similar to I Zw 1. We fit that spectrum with our template (a), with a template based on line intensities from I Zw 1 (Dong et al. 2008) (b), and with a template calculated by the CLOUDY
Table 12
Parameters Used in Analyses of 302 AGN Samples

| Name                  | $z$   | $\log (\lambda L_{5100})$ | $L_{H\beta_{\text{total}}}$ $(10^{40} \text{ erg s}^{-1})$ | $\text{FWHM } H\beta^a$ (km s$^{-1}$) | $w H\beta$ NLR$^b$ (km s$^{-1}$) | Shift H$\beta$ NLR$^c$ (km s$^{-1}$) | H$\beta$ NLR/H$\beta_{\text{total}}$ | w H$\beta$ ILR (km s$^{-1}$) | shift H$\beta$ ILR (km s$^{-1}$) | H$\beta$ ILR/H$\beta_{\text{total}}$ |
|-----------------------|-------|-----------------------------|-------------------------------------------------|--------------------------------------|----------------------------------|-----------------------------------|---------------------------------|----------------------------------|----------------------------------|----------------------------------|
| 000011.96+0000225.29  | 0.478863 | 45.3826                     | 856.7333                                      | 2835.2375                            | 498.5579                         | $-105.7368$                       | 0.0076                          | 1245.3918                         | 529.8802                         | 0.3365                          |
| 001224.03−102226.29   | 0.228075 | 45.1422                     | 591.3836                                      | 2954.4480                            | 377.8284                         | 223.7951                          | 0.0261                          | 1285.4801                         | $-1606.9775$                     | 0.2439                          |
| 001335.38−095120.92   | 0.061570 | 44.0851                     | 29.5634                                       | 3523.3501                            | 172.2847                         | 174.0595                          | 0.0095                          | 1975.1616                         | 205.5797                         | 0.6776                          |
| 003618.41−105503.04   | 0.408479 | 45.4659                     | 1106.6096                                     | 3246.2611                            | 245.4581                         | 217.2596                          | 0.0096                          | 1672.2153                         | 132.8410                         | 0.5109                          |
| 004222.29−103743.70   | 0.423970 | 45.7358                     | 2176.6337                                     | 2900.9095                            | 313.0313                         | 292.0068                          | 0.0138                          | 1431.1402                         | 55.9203                          | 0.4321                          |
| 005812.85+160201.37   | 0.210642 | 45.2320                     | 707.2841                                      | 3936.3637                            | 278.4203                         | 156.4947                          | 0.0096                          | 2262.8155                         | 39.5246                          | 0.7551                          |
| 012159.82−010224.35   | 0.054234 | 44.2039                     | 58.2980                                       | 4217.2466                            | 226.8500                         | 106.1595                          | 0.1208                          | 2469.0427                         | 380.6375                         | 0.6997                          |
| 013418.19+001536.76   | 0.399966 | 45.6719                     | 2193.5488                                     | 4562.5384                            | 376.7642                         | 409.5435                          | 0.0204                          | 1740.6250                         | $-87.2726$                       | 0.2812                          |
| 014631.99+135506.34   | 0.688737 | 45.9144                     | 2420.6242                                     | 3593.5713                            | 113.2796                         | 45.6614                           | 0.0087                          | 1913.9080                         | 325.8444                         | 0.5801                          |
| 014723.28+144320.92   | 0.432697 | 45.1977                     | 365.7338                                      | 1657.0512                            | 217.5084                         | 269.9151                          | 0.1000                          | 671.3043                          | 47.7360                          | 0.2271                          |
| 014942.51+001501.73   | 0.552141 | 46.0557                     | 4681.0997                                     | 3940.7601                            | 494.1209                         | 96.5871                           | 0.0348                          | 2157.2436                         | 364.4667                         | 0.6578                          |
| 015950.24+002340.91   | 0.162741 | 45.2646                     | 677.2004                                      | 2970.4073                            | 294.6930                         | 196.7538                          | 0.0655                          | 1716.0900                         | 207.0487                         | 0.6449                          |
| 020039.16−084555.01   | 0.431919 | 45.2859                     | 512.0838                                      | 1589.0594                            | 188.2487                         | 133.3627                          | 0.0603                          | 967.1185                          | 349.9747                         | 0.4435                          |
| 020435.19−093155.02   | 0.623004 | 45.6721                     | 1345.1493                                     | 2072.8652                            | 116.4124                         | 335.5667                          | 0.0145                          | 1094.7521                         | 306.1241                         | 0.4650                          |
| 021707.88−084743.41   | 0.291441 | 45.2660                     | 335.3650                                      | 2347.9672                            | 187.1275                         | 111.6547                          | 0.0149                          | 1183.1579                         | 146.4486                         | 0.4298                          |

Notes.

*a* Only broad $H\beta$ components included.

*b* Doppler width of $H\beta$ NLR and central [O III] components.

*c* Shift of $H\beta$ NLR and central [O III] components.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Figure 23. Examples of fits to SDSS J020039.15−084554.9: (a) with our template, (b) with the empirical template of Dong et al. (2008), and (c) with the theoretical template of Bruhweiler & Verner (2008). Since this AGN has iron emission equally strong in blue and red iron bumps (as I Zw 1), all three models fit the observed lines well.

Figure 24. Examples of fits to SDSS J141755.54 + 431155.8: (a) with our template, (b) with the empirical template of Dong et al. (2008), and (c) with the theoretical template of Bruhweiler & Verner (2008). In this object, iron emission is a bit stronger in blue than in red. Our model fits this spectrum slightly better than the other two.

Figure 25. Examples of fits to SDSS J111603.13 + 020852.2: (a) with our template, (b) with the empirical template of Dong et al. (2008), and (c) with the theoretical template of Bruhweiler & Verner (2008). In this object, iron emission is much stronger in blue than in red bump. Our model shows disagreement for lines whose relative intensity is taken from I Zw 1, but the other three wavelength regions based on our three line groups fit the observed Fe ii well. The other two models cannot fit this kind of Fe ii emission well.

The relative intensities of Fe ii lines

To estimate the relative intensities of Fe ii lines within the three groups, we stated that the intensity of a line \( (m \rightarrow n) \) should be proportional to the number of emitters \( (N_n) \) (Osterbrock 1989; Griem 1997), i.e., for optically thin plasma (for Fe ii lines) one can write: 

\[
I_{mn} = \text{const} \cdot \frac{2}{\pi^2} \int_0^\infty N_n dx,
\]

APPENDIX C

THE RELATIVE INTENSITIES OF Fe ii LINES
\( A_{mn} \) is the probability of the transition, \( \lambda_{mn} \) is the transition wavelength, and \( \ell \) is the depth of the emitting region.

Of course, the density of emitters can be non-uniform across the region, but we can approximate here that it is uniform, and in the case of non-thermodynamical equilibrium it could be written (Osterbrock 1989) as

\[
N_m \sim b(T, N_e)g_m \exp(-E_{mn}/kT),
\]

where \( b(T, N_e) \) represents deviation from thermodynamical equilibrium. In the case of lines which have the same lower level, one may approximate the ratio as (Griem 1997)

\[
\frac{I_1}{I_2} = \frac{b_1(T, N_e)}{b_2(T, N_e)} \left( \frac{\lambda_2}{\lambda_1} \right)^3 \frac{f_1}{f_2} \frac{g_1}{g_2} \cdot e^{-\left(E_1-E_2\right)/kT}. \tag{C1}
\]

Assuming that \( \frac{b_1(T, N_e)}{b_2(T, N_e)} \approx 1 \) we obtained Equation (1) for estimation of line ratios within one group.

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