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AN ANALYSIS OF THE SPECTRA OF THE SEYFERT GALAXIES MARKARIAN 79 AND I Zw 1

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ABSTRACT

Markarian 79 and I Zw 1 are type 1 Seyfert galaxies with strong emission lines of Fe II. A synthesis of the spectrum of Mrk 79 shows that the Fe II lines have the same profiles as the broad components of the hydrogen lines. As first reported by Phillips, the [O III] and [Ne III] lines in I Zw 1 have a slightly smaller redshift (0.0587) than that for the permitted lines (0.0608) and lines of [O I], [O II], etc. There probably is an additional component in the [O III] and [Ne III] lines with an even smaller redshift (0.0548). In I Zw 1 there is good evidence for emission lines of [Fe II]. In Mrk 79 the broad-line region has an electron density N_e greater than 10^8 cm^{-3} in the ionized hydrogen region, and near 10^7 cm^{-3} in the neutral zone. The high-ionization narrow-line region has $N_e \approx 10^5$ cm^{-3} and an electron temperature T_e in the range of 20,000–30,000 K. Densities in the low-ionization narrow-line region are probably between 10^3 and 10^4 cm^{-3}. The broad (permitted) line region in I Zw 1 has $N_e \approx 10^7$ cm^{-3} on the basis of the presence of [Fe II] lines. The high-ionization narrow-line region has $N_e \approx 10^6$ cm^{-3}. Observations made outside the nucleus of Mrk 79 show average forbidden emission-line velocities which are the same as in the nucleus. There is some evidence based on the absorption H and K lines of Ca II for galactic rotation. A spectrum taken outside the nucleus of I Zw 1 shows H and K of Ca II with the same velocity as the permitted lines and low-ionization forbidden lines in the nucleus region.

Relative transition probabilities for many of the Fe II emission lines seen in Seyfert galaxies have been measured by Ferris and Whaling at the California Institute of Technology. The results are given in a table.

Subject headings: galaxies: individual — galaxies: redshifts — galaxies: Seyfert — spectrophotometry

I. INTRODUCTION

Following the identification of emission lines of Fe II in 3C 273 (Wampler and Oke 1967) and in I Zw 1 (Sargent 1968), it has become clear that Fe II emission is a common occurrence in type 1 Seyfert galaxies and sometimes in quasars (Osterbrock 1977; Phillips 1977, 1978*a*). Perhaps the most useful information which can be gained from the Fe II lines is the estimate of the electron density, since the lower levels of the Fe II transitions are metastable and connected to the ground levels by forbidden transitions which are in the visual part of the spectrum. It is therefore important to determine whether [Fe II] lines are absent or present. It is also important to ascertain whether the Fe II emission lines are generated by the gas which produces the broad permitted lines or the narrower forbidden ones. This can be done by comparing line profiles, but it is difficult because of serious blending of lines.

A major question is how the Fe II lines are produced. One mechanism, first suggested by Wampler and Oke (1967), is resonance fluorescence, where continuum radiation near 2400 Å excites the Fe II atoms to levels which feed the Fe II emission transitions. This requires a substantial optical depth in the resonance lines, since the branching ratio for the upper level is very unfavorable to the observed visual Fe II transitions. Collisional excitation by electrons can also produce strong Fe II lines (Boksenberg *et al.* 1975; Boksenberg and Netzer 1977). Fe II emission can also be produced by radiative recombination but, unless the abundance of iron is extremely high, it will not be important. Phillips (1978*b*) has compared these three ways of generating Fe II emission and concludes that resonance fluorescence is the most likely mechanism. Adams (1975) has studied the scattering problem of Fe II emission lines. It is now possible, using *IUE*, to observe the spectrum of objects such as I Zw 1, Mrk 79, and 3C 273 in the region where the resonance Fe II lines are located. This should help to distinguish between resonance fluorescence and collisional excitation mechanisms.

In this paper a study is made of the spectrum of Mrk 79 (Markarian 1969) and a comparison is made with a similar study, using similar data, of I Zw 1 (Zwicky 1971). The object I Zw 1 has also been studied in detail by Phillips (1976, 1978*a*). A superficial comparison of these two objects brings out the following points: (1) Both objects have broad permitted lines and narrower forbidden ones. (2) The broad lines in Mrk 79 are 3 to 4 times as broad as

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those in I Zw 1. (3) Both galaxies have very strong Fe II lines and the stronger forbidden lines such as those of [O III], [O II], [Ne III], etc., are present. (4) I Zw 1 is 12 times as luminous as Mrk 79. (5) The relative continuum spectral energy distributions of the objects are similar, with a modest slope in the visual and red and flat in the violet.

II. OBSERVATIONS

Observations were made with the low-resolution digital spectrograph attached to the 5 m Hale telescope. The spectrograph was used with a 60″ long slit of width 0″.9. The detector was a cooled SIT vidicon which yields, with the gratings used, a dispersion scale of 5 to 6 Å per pixel and a resolution of about 1.5 pixels. The galaxies were normally trailed along the slit and sky was subtracted by using the exposure on the part of the slit with no galaxy image. Since a slit was used, the spectra are not suitable for absolute spectrophotometry, and consequently only equivalent widths of lines can be derived. To convert the equivalent widths to absolute fluxes, energy distributions of both objects were measured with the multichannel spectrometer.

The multichannel observations of Mrk 79 were obtained on 1970 November 18–19. The seven slit spectra were secured on 1976 January 30–31, December 17–18, and December 19–20, and covered the wavelength range from 3800 to 6900 Å. Multichannel observations of I Zw 1 were obtained on 1969 October 4–5 and 1978 July 11–12, while the nine slit spectra were exposed on 1975 October 4–5, 1976 August 25–26, and August 26–27. The two multichannel observations of I Zw 1 show no change in magnitude over the 9 year interval.

In the case of Mrk 79, slit spectra were also taken, using an east-west slit displaced 6″ south or north of the nucleus. One spectrum of I Zw 1 was taken with an east-west slit positioned 2″ north of the nucleus under conditions of excellent seeing. These off-nucleus spectra are discussed in a separate section.

III. THE EMISSION-LINE SPECTRUM

Both Mrk 79 and I Zw 1 are typical type 1 Seyferts in the sense that the Balmer and helium lines are very broad, while all the forbidden lines are narrower. It is necessary first to determine whether the Fe II lines have narrow or broad profiles; this is not easy, since the lines are numerous and badly blended. The fact that the groups of Fe II lines are completely blended together in Mrk 79, whereas they are partly resolved in I Zw 1, suggests that the Fe II lines have broad profiles, since the broad profiles are very different in width in the two objects.

Experiments using a multiple linear regression program (described below) to synthesize the spectra of Mrk 79 and I Zw 1 confirm that the Fe II lines can be fitted with the broad-line Balmer-line profiles for each object, but not with the forbidden-line profiles. It is concluded and assumed below that the Fe II lines have broad-line profiles. The same conclusion has been reached by Phillips (1977).

In the case of Mrk 79, the narrow-line profile was derived by using λλ4959 and 5007 of [O III] and λ3727 of [O II]. These lines all have identical profiles within the accuracy of the data, even though it is expected that [O II] lines may be formed in a volume of gas distinct from that where the [O III] lines are generated. This profile was used for all forbidden lines. The Balmer-line profiles show clear evidence that they consist of both broad and narrow components. One would expect a narrow-line component which is produced by the gas, which also produces the forbidden lines, as well as a broad-line component not represented by the forbidden lines. Further confirmation of this is the fact that an attempt to synthesize the Fe II spectral regions with complete Balmer-line profiles was not successful. Consequently, a broad-line profile was generated by using Hα and Hβ profiles from which a weak narrow-line profile was subtracted; the hydrogen and helium lines were therefore assumed to be composed of both narrow and broad components, while the Fe II lines were assumed to consist of broad profiles only. The two adopted profiles are shown in Figure 1. No allowance has been made for instrumental effects.

For I Zw 1 the broad-line and narrow-line profiles are sufficiently similar that it is pointless to try to divide the hydrogen and helium lines into broad and narrow components. The profile of Hβ was used for all of the permitted lines in the spectrum. The FWHM is 1300 km s^{-1}. In the case of the forbidden lines there is a difficulty because the [Ne III] and [O III] lines have one redshift, $z = 0.0585$, while the other forbidden lines such as [O II] and [S II] have $z = 0.0608$, like the permitted emission lines (Phillips 1976). A narrower profile, with FWHM = 1000 km s^{-1}, was used for all lines with $z = 0.0585$ (that is, [O III], [Ne III]), while the slightly broader profile was used for all lines with $z = 0.0608$. This slightly broader profile may not be appropriate for the [O II] and [S II] lines, but they are

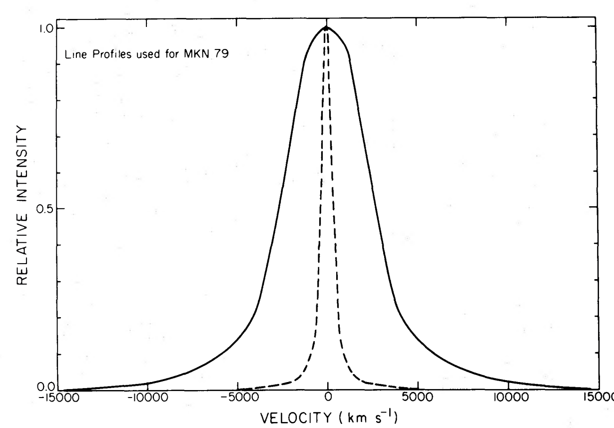

FIG. 1.—Broad- and narrow-line profiles used for synthesis of the spectrum of Mrk 79.

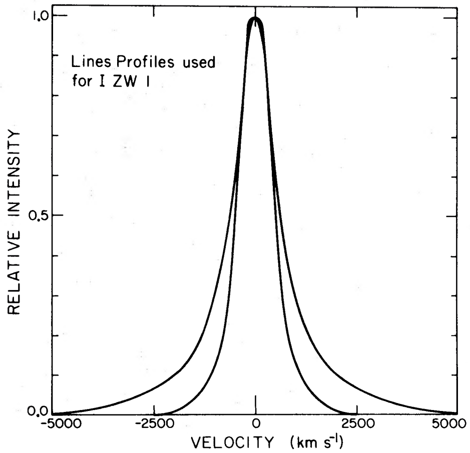

FIG. 2.—Broad- and narrow-line profiles used for synthesis of the spectrum of I Zw 1.

so weak that the choice of profile is of little consequence. The two adopted profiles are shown in Figure 2.

The identification and intensity measurement of the emission lines were accomplished by synthesizing the spectra. After shifting the observed spectrum to a rest wavelength system, it was divided into six separate regions for synthesis. Within each region a list of contributing lines along with their rest wavelengths was drawn up. In many cases, including the forbidden lines in Mrk 79 and nearly all lines in I Zw 1, the lines could be readily identified individually. In Mrk 79, however, many of the Fe II lines are completely blended; the list of lines therefore was taken from the multiplets expected to contribute on the basis of identifications in sharper-lined objects such as I Zw 1.

The synthesis of each spectral region was accomplished by a multiple linear regression subroutine. The only variables allowed were the intensities of the lines, i.e., scaling the standard profiles assigned to each spectral line, and small shifts of a few angstroms, necessitated by wavelength errors in the initial data. The best fit was established by using least squares. For Mrk 79 the continuum was assumed to be linear in each spectral region, and the best fit to the continuum was also generated by the program. For I Zw 1, which was analyzed with an improved program, the continuum in each region was allowed to be of second order and was also optimized by the synthesizing program. Once the synthesis was complete, the equivalent widths could be readily calculated in terms of the fitted continuum and could be scaled to observed equivalent widths by multiplication by $1 + z$. The above procedure was carried out for each of the six spectral regions, using three sets of averaged spectra. The results are given in Tables 1 and 2, where the rest wavelength, identification (including multiplet numbers for Fe II or [Fe II]; Moore 1945), and redshifted equivalent widths are listed. A *b* in the Notes column denotes a line which is so badly blended with other lines and so weak that there is no significant peak at the line center. A line which is in the wing of another stronger line and which produces a broadening of the line or an asymmetry in the profile is also designated with a *b*. A few weak lines used in the least-squares fitting but too questionable to identify are not included. In the case of long blended regions of spectrum, all equivalent width in the blend is accounted for. Two lines in Mrk 79 are not identified. One of these, at 6223 Å, is narrow and possibly identifiable as [K V]. Several lines in I Zw 1 remain unidentified. They are present in η Carinae, and Thackeray (1953) has suggested possible identifications. Thackeray identifies λ5673 as [Fe II]; Garstang (1962) has calculated its transition probability. There appear to be two additional unidentified lines at 5455 and 5504 Å.

The observed and synthesized spectra of all six regions for Mrk 79 are shown in Figures 3 to 8 for one of the three spectra analyzed. For I Zw 1 three spectral regions are shown in Figures 9 to 11. In the case of I Zw 1, completely independent spectra of comparable quality have already been published (Phillips 1976). A detailed comparison of Phillips's data and the data in Figures 9 to 11 show that subtle line asymmetries and very weak features usually duplicate each other in detail.

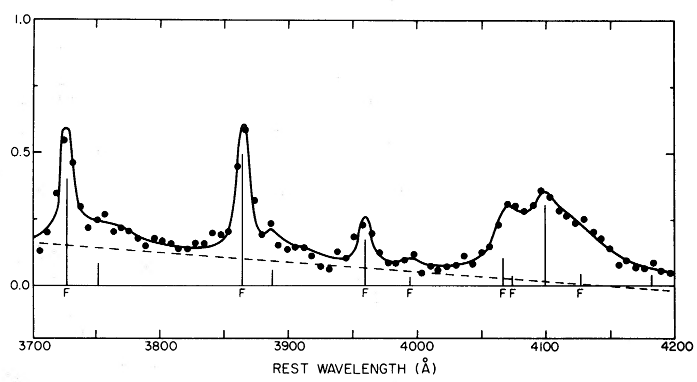

FIG. 3.—The solid curve is the synthesized spectrum and the solid dots denote the observed spectrum of Mrk 79. The vertical axis is in intensity units. Intensities of contributing lines are indicated by the heights of the vertical lines. Forbidden lines are marked *F*. The broken, nearly horizontal line is the fitted continuum level. The data represent only one of several spectra analyzed.

TABLE 1

LINE INTENSITIES FOR MARKARIAN 79

Wavelength Å	Identification	E.W.* Å	j†	σ†	Notes
3726, 29...	[O II]	4.5	38	2	
3754, 59...	O III	6.5	54	21	b
3791.......	O III	3.3	26	5	b
3868.......	[Ne III]	5.4	41	7	
3889.......	He I, H 8	6.0	45	7	
3968.......	[Ne III], Hε	7.0	52	19	
4068, 76...	[S II]	1.8	12	2	
4101.......	Hδ (broad)	24.2	166	22	
4101.......	Hδ (narrow)	1.2	8	2	b
4340.......	Hγ (broad)	52.6	341	2	
4340.......	Hγ (narrow)	1.5	10	2	b
4363.......	[O III]	2.4	15	3	
4489, 91...	Fe II 37	2.3	15	2	b
4508.......	Fe II 38	3.1	19	3	b
4515, 20...	Fe II 37	4.3	27	4	b
4522.......	Fe II 38	4.6	29	4	b
4549, 55...	Fe II 37, 38	2.0	12	8	b
4576.......	Fe II 38	3.1	19	2	b
4583.......	Fe II 37, 38	11.1	68	8	b
4620.......	Fe II 38	1.9	12	4	b
4629.......	Fe II 37	4.3	26	10	b
4666.......	Fe II 37	10.5	63	16	b
4686.......	He II	1.9	11	1	
4711.......	[A IV]	0.6	3	1	
4740.......	[A IV]	0.7	4	1	
4861.......	Hβ (broad)	159.0	928	11	
4861.......	Hβ (narrow)	5.9	35	6	b
4894.......	[Fe VII]	3.7	21	4	
4923.......	Fe II 42	9.1	53	4	b
4958.......	[O III]	26.7	153	5	
5007.......	[O III]	63.0	361	37	
5018.......	Fe II 42	13.1	74	41	b
5045.......	-	12.4	70	15	b
5158.......	[Fe VII]	1.0	6	2	
5169.......	Fe II 42	9.3	52	5	b
5197.......	Fe II 49	4.6	26	3	b
5234.......	Fe II 49	5.6	31	23	b
5264.......	Fe II 48	0.9	5	2	b
5276.......	FeII 49 ,[FeVII]	3.1	17	9	b
5308.......	[Ca V]	1.1	6	1	b
5316, 26...	Fe II 48, 49	15.9	88	18	b
5362.......	Fe II 48	7.2	40	14	b
5414.......	Fe II 48	2.1	11	3	b
5425.......	Fe II 49	1.1	6	2	b
5723.......	[Fe VII]	1.6	9	3	
5876.......	He I (broad)	32.9	180	7	
5876.......	He I (narrow)	1.7	9	2	b
6085.......	[Ca V],[Fe VII]	3.6	20	4	
6223.......	-	2.3	13	1	
6300.......	[O I]	7.4	41	2	
6363.......	[O I]	5.3	30	6	
6548.......	[N II]	20.9	120	8	b
6562.......	Hα (broad)	718.0	4130	113	
6562.......	Hα (narrow)	58.0	334	19	b
6583.......	[N II]	43.0	249	42	
6717.......	[S II]	13.7	81	15	b
6731.......	[S II]	9.9	58	5	b

* Observed Frame.

† Units of 10^{-15} ergs sm^{-2} s^{-1}.

TABLE 2
LINE INTENSITIES FOR I ZW 1

Wave-length Å	Identification	E.W.* Å	j†	σ†	Notes	Wave-length Å	Identification	E.W.* Å	j†	σ†	Notes
3479...	FeII 4	2.4	32	13	b	4731...	FeII 43; [AIV]0.0587	2.3	22	1	
3487...	FeII 4,16	6.6	86	13		4823...	-	4.9	46	5	
3503...	FeII 4,16	2.3	30	11	b	4861...	Hβ	41.3	386	29	
3562...	-	1.6	20	10		4889...	[FeII] 4F	2.9	27	13	
3727,29	[O II]	5.1	62	22		4924...	FeII 42	11.8	109	7	
3749...	-	2.7	32	3		4948...	[OIII] 0.0587	4.7	43	5	
3764...	O III?	3.2	38	1		4978...	[OIII] 0.0548	5.3	48	3	b
3824...	FeII 27	0.8	10	1		4996...	[OIII] 0.0587	14.1	128	2	
3848...	[NeIII] 0.0548	1.6	19	5	b	5018...	FeII 42	9.3	84	2	
3862...	[NeIII] 0.0587	4.6	54	5		5132...	FeII 35?	3.2	28	4	
3888...	H8; HeI	2.3	27	7		5158...	[FeII] 18F, 19F	6.0	53	16	b
3938...	FeII 3	1.5	17	10		5169...	FeII 42	7.2	63	6	b
3947...	[NeIII] 0.0548	0.4	4	2	b	5197...	FeII 49	7.1	62	3	
3961...	[NeIII] 0.0587	1.9	22	7	b	5234...	FeII 49	7.0	60	1	
3970...	Hε	2.3	27	1	b	5265...	FeII 48	7.5	64	11	
4012...	-	1.7	19	6		5275...	FeII 49	6.4	55	1	b
4026...	HeI	1.6	18	7		5284...	FeII 41	3.5	30	5	b
4068...	[SII]	2.4	27	6	b	5316...	FeII 48,49	10.3	87	12	
4076...	[SII]	1.1	12	5	b	5337...	FeII 48	3.1	26	3	b
4101...	Hδ	7.6	85	6		5363...	FeII 48	5.5	46	4	
4126...	FeII 27,28	4.0	44	13		5376...	[FeII] 19F	1.5	12	4	b
4177...	FeII 27,28	8.0	87	12		5414...	FeII 48	1.6	13	1	b
4233...	FeII 27	4.4	47	1		5425...	FeII 49	6.8	56	4	
4244...	[FeII] 21F	2.9	31	5	b	5477...	FeII 49	1.6	13	5	
4273...	FeII 27	2.0	21	5	b	5534...	FeII 55	8.1	64	3	
4287...	[FeII] 7F	3.0	32	2		5658...	-	1.9	15	7	
4296...	FeII 28	2.1	22	2	b	5673...	[FeII]	3.1	24	5	
4303...	FeII 27	2.9	30	4		5754...	[NII]	2.2	17	4	
4320...	[FeII] 21F; FeII 32	4.2	44	1	b	5876...	HeI	8.7	65	4	
4340...	Hγ	12.7	134	16		5893...	NaI	6.4	46	5	
4351...	FeII 27	6.5	68	9	b	5991...	FeII 46	4.0	28	1	
4358...	[OIII], z=0.0587	5.1	53	3	b	6044...	FeII 46	3.4	23	7	
4369...	FeII 28	2.7	28	8	b	6084...	FeII 46	4.4	30	9	
4385...	FeII 27	5.0	52	7		6130...	FeII 46	2.9	19	12	
4416...	FeII 27	7.7	80	4		6150...	FeII, 46, 74	6.4	42	12	
4454...	[FeII] 6F, 7F	4.9	50	2		6180...	FeII 46	5.5	36	8	
4471...	HeI; FeII 37	4.4	44	2		6238...	FeII 74	4.0	27	82	b
4491...	FeII 37	5.8	59	2		6247...	FeII 74	5.3	34	8	b
4512...	FeII 37, 38	5.6	56	1		6300...	[OI]	3.9	25	3	
4522...	FeII 37, 38	7.8	79	1		6363...	[OI]	13.1	81	7	
4549...	FeII 38	6.2	62	16		6417...	FeII 74	12.9	79	16	b
4555...	FeII 37	5.6	56	19	b	6432...	FeII 40	13.8	83	18	b
4583...	FeII 37, 38	11.1	111	6		6456...	FeII 74	18.4	110	44	b
4620...	FeII 38	4.8	47	9	b	6516...	FeII 40	8.5	50	16	b
4629...	FeII 37	10.0	98	6		6548...	[NII]	13.0	73	50	b
4657...	FeII 43	4.6	45	6		6562...	Hα	414.0	2375	615	
4666...	FeII 37	4.0	38	1	b	6583...	[NII]	41.0	235	157	b

* Observed frame. † Units of 10^{-15} ergs cm^{-2} s^{-1}.

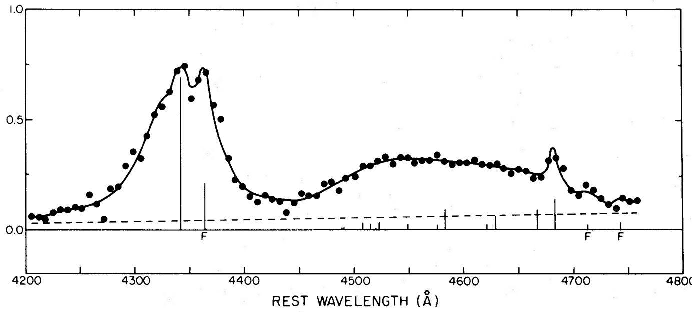

FIG. 4.—Same as Fig. 3

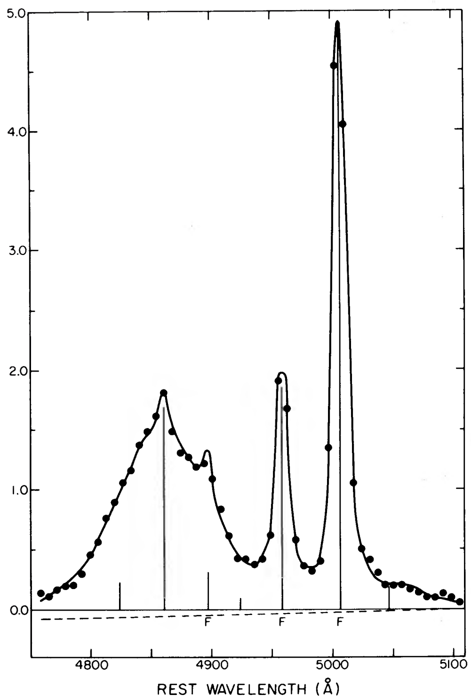

FIG. 5.—Same as Fig. 3

The final step in the synthesis is to convert the equivalent widths into line intensities. Although 40 Å bandpasses were used for the multichannel spectrometer observations of these two objects, the instrumental response is essentially rectangular and the edges of each band are known to about 2 Å. Consequently, the continua defined by the least-squares syntheses and shown in Figures 3 to 11 can easily be located on the absolute energy distribution from the multichannel spectrometer. The resulting continuum is shown in Figure 12 for Mrk 79. The continuum for I Zw 1 is derived in the same way and is based partly on the multichannel energy distribution published by Oke and Shields (1976). Once the continuum is defined, then all emission-line equivalent widths can be converted to absolute intensities, j ergs cm^{-2} s^{-1}. These are given in Tables 1 and 2. These tables also give estimated errors for j based primarily on the agreement for each tabulated line among the different spectra analyzed.

Line intensities for Mrk 79 have also been measured by Osterbrock (1977). The differences between his and our measurements is typically 30% or less for stronger lines, a factor 2 for weak lines and lines near the wavelength limits of the observations, and up to a factor 3 for very badly blended lines. The largest differences occur for lines above 6200 Å. A comparison with intensities given by Neugebauer *et al.* (1976) for Mrk 79 shows differences of up to 60%; the Hα measurements are very discordant. These differences can be traced largely to differences in placing of the continuum for the multichannel observations, which, for objects such as MrK 79, is very difficult, as demonstrated by Figure 12.

Phillips (1978*a*) has made a detailed study of the spectrum of I Zw 1. This object provides the basis for a detailed comparison of Lick and Palomar data, since most of the lines are at least partially resolved. There is a substantial difference in the equivalent width

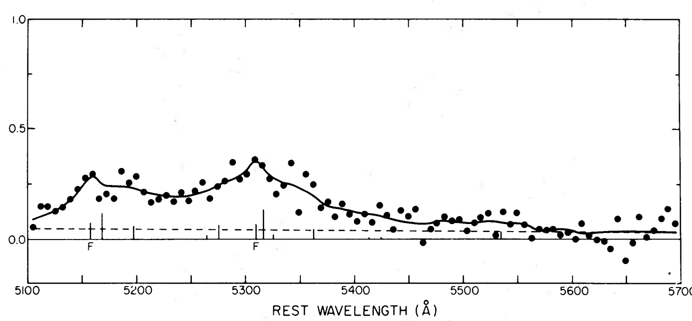

FIG. 6.—Same as Fig. 3

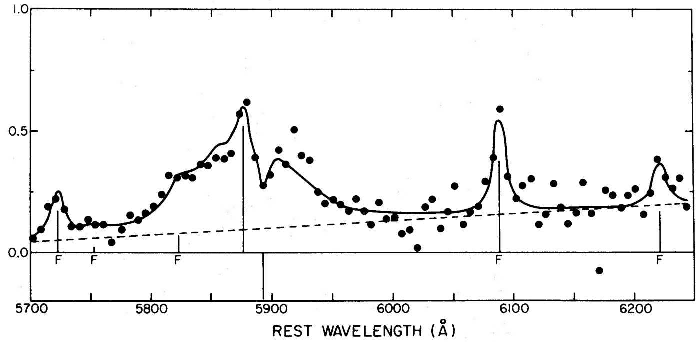

FIG. 7.—Same as Fig. 3

of Hβ in the two sets of data. Phillips gives 68 Å, while our data give 46.2 Å for the comparable spectral range. If we normalize all of Phillips's intensities given relative to Hβ, to allow for this difference, we find excellent agreement for virtually all other lines. For instance, the average difference for 43 Fe II weak and strong lines is 30%. For the remaining lines the average difference is 20%, the worst two cases being the [O III] lines λλ4959, 5007. We feel that our results for these last two lines mentioned are accurate, since the fitting procedure gives a ratio of 1:3 as required. The generally good agreement indicates that the two synthesizing techniques are comparable and give reliable results. The disagreement for Hβ and the [O III] lines is puzzling, and may have to do with the way in which the continuum is chosen in this spectral region.

IV. EMISSION-LINE ANALYSIS

a) *Markarian 79, Narrow Lines*

As noted above, it was found necessary in the fitting procedures to assume that the Balmer lines consisted of both broad and narrow components. The decomposition of the Balmer lines into broad and narrow components is, however, very uncertain, and the formal Balmer decrement for the narrow lines, which disagrees with recombination theory, should not be taken seriously. This is partly because the decomposition itself is uncertain and also because the exact shape of the broad-line component near the line center is poorly defined.

The ratio of intensities of the narrow lines is similar within a factor 2 to the average for type 2 Seyferts (Neugebauer *et al.* 1976). The [Ar IV] lines λλ4711, 4740 can be used to estimate the density. The observed ratio $j_{4711}/j_{4740} = 0.8$. In the low density limit the ratio should be 1.5; at high densities it decreases to 0.12. Since the lines are very weak, it is not certain whether the observed ratio is significantly different from the low density ratio. The ratio does indicate that $N_e \lesssim 10^5$ with the equality if the observed ratio is indeed 0.8. The ratio of the [O III] lines $(j_{4959} + j_{5007})/j_{4363} = 34 \pm 10$. In the low density limit, i.e., $N_e \lesssim 10^5$, this ratio implies an electron temperature of 20,000 to 30,000 K. The temperature is 10,000 K only if $N_e \approx 10^6$ cm^{-3}. Since [Ar IV] and [O III] probably come from the same volume, then the [Ar IV] lines confirm that the low density limit is correct and that the temperature is in the range 20,000–30,000 K.

The [N II] lines λλ6548, 6583 are present (Fig. 8) and their intensities are probably accurate to perhaps 25%. The λ5755 line is weak and has an intensity less than 5×10^{-15} ergs s^{-1} cm^{-2}. This leads to a ratio

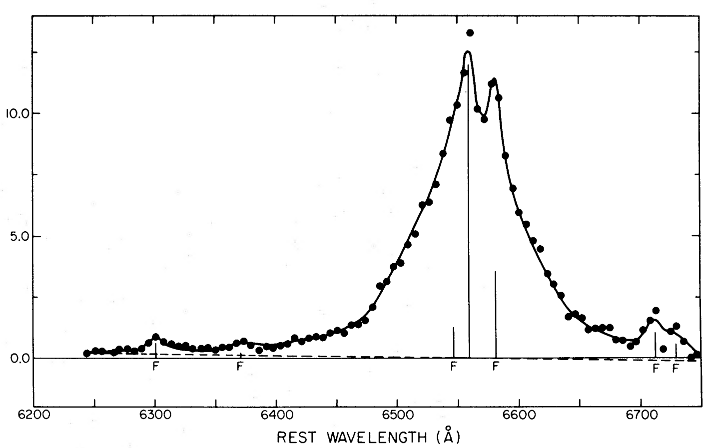

FIG. 8.—Same as Fig. 3. Note the absorption at the Na I D lines

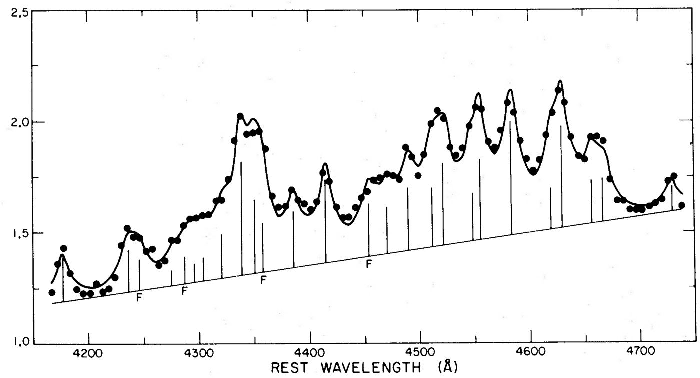

FIG. 9.—Same as Fig. 3, but for I Zw 1

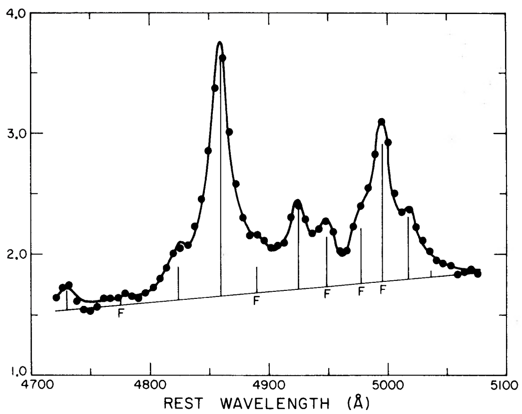

FIG. 10.—Same as Fig. 3, but for I Zw 1

$(j_{6548} + j_{6583})/j_{5755} > 60$. In the low density limit, $N_e \leq 10^3$, this indicates $T_e < 15{,}000$ K. If $T_e = 10{,}000$ K, then $N_e \leq 10^4$ cm^{-3}.

Both the red and blue [S II] lines are present with an intensity ratio $(j_{6716} + j_{6731})/(j_{4068} + j_{4076}) = 12$. In the low density limit, i.e., $N_e \leq 2 \times 10^3$ cm^{-3}, this indicates $T_e = 10{,}000$ K. If the densities are higher, the value of T_e will be somewhat smaller.

We conclude that the [O II]–[N II]–[S II] region can be characterized by $T_e \approx 10{,}000$ K and $N_e \approx 10^3$ to 10^4 cm^{-3}.

The only unusual lines in Mrk 79 are those of [Fe VII] and [Ca V]. [Fe VII] is represented by three moderately unblended lines λλ4894, 5158, and 5723. One other line, λ5276, is badly blended with Fe II, while another, λ6085, is blended with [Ca V] (see below). These identifications are secure, since they represent the strongest lines of [Fe VII] expected. [Fe VII] lines are present but weak in many Seyferts (Phillips 1978*a*). The best evidence for [Ca V] is the line at λ6085. Although it is blended with [Fe VII], it is so strong that it must be mostly [Ca V]. The other expected line of [Ca V] is λ5308. There is a sharp peak at this wavelength, indicating the presence of a narrow forbidden line, but it is blended with many broad Fe II lines. The relative line strengths of the [Fe II] and [Ca V] lines are similar to those in NGC 1068 (Shields and Oke 1975).

b) *Markarian 79, Broad Lines*

The broad-line spectrum consists of lines of hydrogen, He I λ5876, O III λλ3754, 3759, 3791, and many lines of Fe II. The Balmer decrement is typical of type 1 Seyferts, having $j_{\mathrm{H}\alpha}/j_{\mathrm{H}\beta} = 4.45$ and $j_{\mathrm{H}\gamma}/j_{\mathrm{H}\beta} = 0.37$. He I λ5876 is 19% as strong as Hβ. He II λ4686 is listed in Table 1. It had to be fitted, however, by a narrow-line profile, since the feature is sharp (see Fig. 4). Since He II should be associated with the broad-line region, it is quite possible that the identification is not

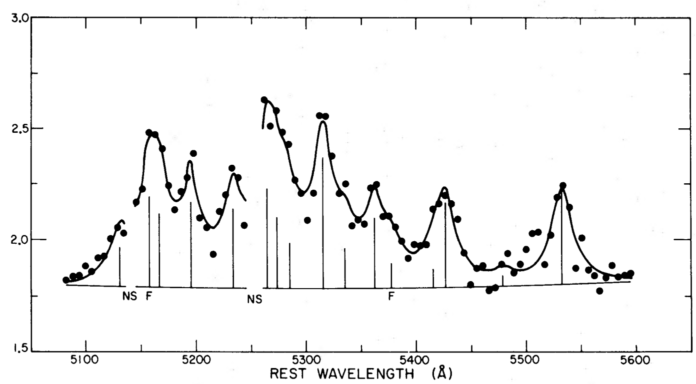

FIG. 11.—Same as Fig. 3, but for I Zw 1

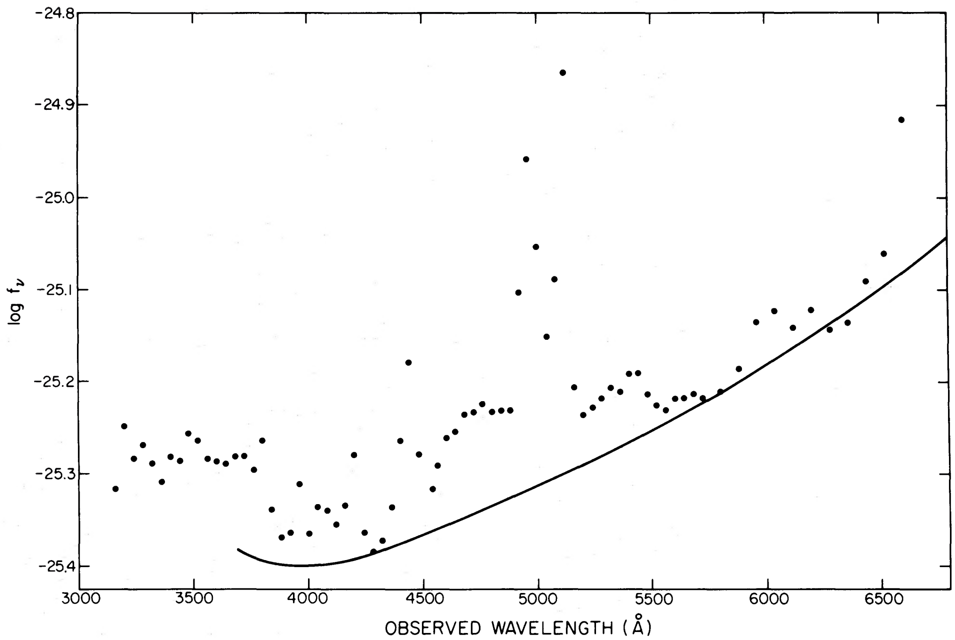

FIG. 12.—The absolute spectral energy distribution of Mrk 79. The flux f_ν is in ergs s^{-1} cm^{-2} Hz^{-1}. *Solid line*, continuum derived from the spectrum synthesis.

correct for this narrow line. The Fe II lines identified are all from multiplets 42, 48, 49, 37, and 38. These are the strongest multiplets seen in most other Fe II objects. Lines from multiplets 27 and 28 are genuinely weak, since some of them occur in spectral regions where they can readily be measured. A search for [Fe II] lines was made by inserting the stronger ones into the spectrum synthesis program. No evidence of [Fe II] was found although, because the lines are so broad, the upper limits are not very significant.

It should be noted that all spectra show an absorption feature at the redshifted position of the D lines of Na I (see Fig. 7). The fitting program gives an equivalent width of 2.3 Å. This is comparable to the largest equivalent widths of interstellar sodium lines seen in spectra of stars in our Galaxy and corresponds to a minimum of 10^{13} atoms cm^{-2} in the line of sight.

c) I Zw 1, Broad Lines

The ratio of Hα to Hβ is 6.1, while that for Hγ/Hβ is 0.35. These differ somewhat from those of Phillips (1978*a*) because of the discrepancy in Hβ already discussed. Since the broad lines in I Zw 1 are still moderately narrow, the identification of other lines is relatively easy and the vast majority are due to Fe II. The only He I line seen is λ5876. He I lines such as $\lambda\lambda$3889, 4471, etc., may be present but are blended with the identified lines. The He II λ4686 line is not seen, although it is in a spectral range where it would be moderately easy to detect (see Fig. 9). There is also strong evidence for the D lines of Na I in emission in the wings of He I λ5876. This line was also noted by Phillips (1976). We do not confirm the Ca II K emission identified by Phillips. The line is too far to the red and is undoubtedly Fe II (3).

d) I Zw 1, Narrow Lines

Phillips (1976) has demonstrated that the [O III] and [Ne III] lines have a lower redshift ($z = 0.0587$) than the other lines. Our spectra confirm this. There is the possibility of another component with a smaller redshift still, i.e., $z = 0.0548$. This component for λ5007 of [O III] is seen in Figure 10 at 4977 Å as an asymmetry in the main line. A similar asymmetry is seen in the [Ne III] λ3868 line. [Ar IV] λ4740 may be present at 4730 Å in Figure 10, in which case it has the same redshift as the [O III] and [Ne III] lines. This same feature, however, can also be identified with a line in multiplet 43 of Fe II. The only other line of this Fe II multiplet is at 4657 Å. The problem with the Fe II identification is that λ4657 is observed to be stronger than λ4730, whereas the opposite probably should be true (Moore 1945). If the line is [Ar IV], then the other [Ar IV] line which should occur at a rest wavelength of 4701 Å is much weaker (see Fig. 9), which requires N_e to be greater than 10^5 cm^{-3}. The ratio $(j_{4959} + j_{5007})/j_{4363}$ is 4.1, with a possible range from 2.6 to 9 (the small tabulated error for j_{4363} is probably fortuitous). For $T_e = 10{,}000$ K this implies $N_e \approx 10^7$, while for $T_e = 25{,}000$ K, $N_e \approx 10^6$ to 10^7 cm^{-3}. This result is in agreement with the results for [Ar IV] if the [Ar IV] identification is correct.

Lines of [O II], [S II], and [N II] all have the same redshift as the permitted lines. The only line ratio which can be measured from our data is $(j_{6548} + j_{6583})/j_{5755}$. This ratio is 18 with a possible range for 5 to

39 and, although very uncertain, indicates that $N_e \approx 10^{4.5}$ to 10^6 if T_e is 10,000 K. Phillips (1976) notes that the red and blue [S II] lines have similar intensities, indicating $N_e > 10^5$ to 10^6 cm^{-3}.

e) *I Zw 1*, [Fe II] *Lines*

The galaxy I Zw 1 is an excellent object to determine whether lines of [Fe II] are present, since the emission lines are not too broad. Furthermore, weak or blended features seen in our spectra and confirmed by the independent spectra of Phillips (1976, 1977) give more confidence in the reality of such features. The multiplets which would be expected to be present are 4F, 6F, 7F, 18F, 19F, 20F, 21F, and 33F. Expected relative line strengths can be inferred from observations of η Carinae (Thackeray 1953) and from the transition probabilities calculated by Garstang (1962). The strongest lines in multiplet 4F are λλ4890, 4728, and 4640. There is evidence for a weak line at λ4890 (Fig. 10). The line at λ4728 could be due also to Fe II (43) and [Ar IV] (see above). The line λ4640 is in a very crowded spectral region. In 6F the only line not blended with Fe II is λ4458. There is indeed strong evidence that this line is present (see Fig. 9). Another line in 6F is λ4416, which is blended with λ4413 in 7F and λ4416 in 27. The line is observed to be too strong to be accounted for entirely by the permitted line and suggests the presence of the forbidden ones. In 7F only λ4452 provides a clear test; this line is blended with λ4458 in multiplet 6F. The only line in 18F which could be seen is λ5158. In our spectra (Fig. 11) there is a strong line near this wavelength which is too wide to be a single line. This line may be partially resolved by Phillips. The red part of the line is λ5167 of Fe II (42), while the violet part of the line could be λ5158. A strong line at this same wavelength occurs in 19F. Another line in 19F occurs at λ5376. The shape of the spectrum in this region (Fig. 11) suggests that it is present, as does the spectrum by Phillips. There are no suitable lines in multiplet 20F or 33F. The line λ4246 in 21F is on the red side of another line λ4236 of Fe II (27) and is probably present (Fig. 9). This pair of lines is partially resolved by Phillips. All the above evidence suggests that [Fe II] lines are present in the spectrum. They are individually somewhat weaker than the permitted lines, suggesting that some collisional de-excitation or photoionization from the metastable levels occurs. This indicates that the electron density for this gas is close to 10^7 cm^{-3} (Wampler and Oke 1967; Phillips 1978*a*). This density limit presumably applies to the gas which produces the other permitted lines.

Further information concerning the value of N_e comes from the [O III] lines. These lines must be extremely weak in the $z = 0.0608$ system, since they have not been detected. This puts a lower limit on N_e of 10^8 cm^{-3} in the ionized hydrogen region. (The [O III] lines which are present have a different redshift and so should not be considered to be part of the broad-line region.) Since the Fe II and [Fe II] lines must be formed in the part of the cloud where hydrogen is neutral and the [O III] lines come from the ionized hydrogen region of the cloud, one would expect the electron density derived from the Fe II to be substantially lower than that from the [O III] lines.

V. DISCUSSION

It is a general view that type 1 Seyfert galaxies can be characterized by three distinct regions. First there is the broad-line region (BLR), probably considerably smaller than 1 pc in diameter with electron densities greater than 10^8 cm^{-3}. Outside of this is a narrow-line region (NLR), where the [O III], [Ne III], [Ne V], and [Ar IV] are formed and where the electron density is typically 10^6 cm^{-3}. Third, there is an additional low-ionization narrow-line region where lines of [O II], [S II], etc., are generated and characterized by electron densities substantially less than 10^6 cm^{-3}.

Markarian 79 is a typical type 1 Seyfert in which there is a large difference between the breadths of the broad and narrow lines. FWHM values are 5400 and 750 km s^{-1}, respectively. The ionized BLR appears to be typical with values of N_e greater than 10^8 cm^{-3}. The high-ionization NLR has $N_e \approx 10^5$ and $T_e \approx$ 20,000–30,000 K; this value of N_e is somewhat smaller than typical. Densities in the low-ionization NLR are between 10^3 and 10^4 cm^{-3} for T_e = 10,000 K.

The galaxy I Zw 1 is not a typical type 1 Seyfert since the permitted and forbidden lines are of comparable breadth. The FWHM values are 1300 and 1000 km s^{-1}, respectively. In the BLR, where $z =$ 0.0608, the presence of [Fe II] and absence of strong [O III] lines place N_e close to 10^7 cm^{-3} in the neutral hydrogen region and above 10^8 cm^{-3} in the ionized hydrogen zone. The high-ionization NLR, where $z =$ 0.0587, has electron densities of about 10^6 cm^{-3}. The low-ionization NLR, with $z = 0.0608$, has a somewhat lower value of N_e. The difference in velocity between the high-ionization and low-ionization lines confirms that there are two physically distinct regions.

The Fe II emission lines observed in Seyfert galaxies are confined to a group of at most 10 multiplets; the upper levels of these 10 multiplets are confined to six levels. To assist in understanding the mechanism generating these lines a program was initiated by W. Whaling and E. Ferris to measure relative transition probabilities of the lines arising from these six levels. This program is described in the Appendix, which also presents the results. In some cases several observed multiplets have the same upper levels; an example is the group of $z\,^4D^o$ levels which are tied to multiplets 27, 28, and 48. For optically thin radiative processes, the relative transition probabilities indicate the line intensities in the three multiplets. A plot of gA values versus line intensity for I Zw 1 shows a very wide scatter and several serious anomalies. For example, λ4620 of multiplet 38 and λ5420 of multiplet 49 have small gA values but the observed lines are strong. The lines λ4385 and λ4233 of multiplet 27 have large gA values, but the lines are not abnormally strong. These anomalies are much larger than the errors in the A values and observed intensities and they do not appear to be produced by blending of lines. They suggest that simple radiative processes in an optically thin gas are inadequate to explain the observations.

One further glaring problem first pointed out by Phillips (1978*b*) is the very low intensity of lines in multiplets 6 and 7. These transitions come from the same levels as multiplets 37, 38, etc., and have *A* values typically 10 to 100 times larger than those in multiplets such as 37 and 38. Phillips's observations show these lines to be faint, and our multichannel observations show them to be no stronger than those in multiplets 37 and 38. A similar problem exists with λλ4924, 5018, and 5169 of multiplet 42. They rule out optically thin radiative models.

Osterbrock (1977) has shown that for a large sample of Seyfert galaxies there is a good correlation between line strengths in multiplets 37 and 38 and line strengths in 48 and 49. This correlation holds for I Zw 1 and Mrk 79. Multiplets 27 and 28, on the other hand, have line strengths comparable with those in 37 and 38 in I Zw 1 but are much weaker, or even absent, in Mrk 79. There is some indication in the spectra presented by Phillips (1977, 1978*a*) that multiplets 27 and 28 are highly variable, being strong in some objects, such as I Zw 1 and Mrk 478, and weak in others, like Mrk 376.

Phillips (1978*b*) has made models and calculated Fe II line strengths. His optically thin models reflect the problems already mentioned. He has also made optically thick resonance fluorescence models. They have the property of decreasing line intensities in multiplets 6, 7, 27, 28, and 42 relative to those in 37 and 38. These optically thick models therefore fit the observations much better than optically thin ones. It is not clear whether such models can suppress multiplets 27 and 28 to the extent required in Mrk 79.

Phillips (1978*b*) has also discussed the effects of collisional excitation on the Fe II emission-line strengths and points out that such models do not fit the observations as well as the optically thick resonance fluorescent ones. A strong argument against significant collisional excitation is the absence of emission in the Fe II resonance and near-resonance lines in the 2400 Å spectral region. This emission is not seen in 3C 48 or PKS 1510−089 (Phillips 1978*a*). It is also not seen in *IUE* observations of 3C 273 (Boggess *et al.* 1979) or in *IUE* observations of Mrk 79 made by one of the authors. As argued by Boggess *et al.*, the absence of emission probably rules out strong collisional excitation, while the absence of absorption at these same wavelengths does not necessarily rule out resonance fluorescence. The observations appear to favor optically thick resonance fluorescence.

VI. OBSERVATIONS OUTSIDE THE NUCLEUS

Markarian 79 is extended along a line with a position angle of about 65° north through east. Two slit spectra were taken, first with an EW slit located 6″ north of the nucleus, and second, with an EW slit 6″ south of the nucleus. Each spectrum was reduced in two parts, one sampling radiation directly north or south of the nucleus and the second sampling the radiation in the extensions at the 65° position angle. The spectrum directly north of the nucleus shows narrow [O III] λλ4959, 5007 lines and probably also narrow Hα and Hβ lines in emission. The spectrum directly south of the nucleus shows only narrow [O III] lines. Both spectra show H and K of Ca II in absorption and some evidence for the Mg *b* band. The two spectra in the extended regions at the 65° position angle show no emission but do show Ca II H and K, and the Mg *b* band in absorption; one spectrum may show the Na I D lines in absorption. The measured velocities are shown in Table 3, for both the off-nucleus and the nucleus regions. Absorption redshifts are from the H and K lines of Ca II, while the emission ones are from [O III] with [Ne III] λ3869 added when seen. The uncertainties are approximately ±0.0005 in z. Velocities NE and SW of the nucleus show at least the possibility of galactic rotation, with the difference being 400 km s^{-1}. This same range is seen in the absorption redshifts directly north or south of the nucleus. The off-nucleus emission on average is 0.0218, which can be compared with 0.0214 for the nucleus forbidden emission lines; the difference is not significant. The absorption redshifts are on the average slightly lower than the average emission ones by about 0.0012 in z or 360 km s^{-1}. The spectra of the nucleus regions show no velocity difference between the broad and narrow lines.

In the case of I Zw 1, one spectrum was taken with an east-west slit located 2″ north of the nucleus. As expected at this small angular distance from the nucleus, the contamination from the nucleus is severe. One can, however, see the H and K lines of Ca II in absorption. The redshifts for these lines are, respectively, 0.0634 ± 0.001 and 0.0608 ± 0.001, with the latter being more reliable, since the H line can be affected by emission from Hε and λ3968 of [Ne III]. The absorption redshift is consistent with the redshift of the permitted lines in the BLR and the low-ionization NLR lines.

TABLE 3

REDSHIFTS OUTSIDE THE NUCLEUS OF MARKARIAN 79

Type of Line	NE	N	Nucleus	S	SW
Absorption....	0.0199	0.0194	...	0.0211	0.0212
Emission......	...	0.0222	0.0214	0.0214	...

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TABLE 4

Relative Transition Probabilities for Fe II Lines

Upper level	Multiplet	Reference*	λ	A (s^{-1})
$z^4D^o_{1/2}$ ...	38	R (1, 2)	4508.283	7.02×10^5
	27		4385.381	2.54×10^6
	6	(4)	3193.806	2.05×10^8
$z^4D^o_{3/2}$ ...	38	R (1)	4541.523	2.18×10^5
	38		4522.634	3.01×10^5
	27		4303.166	5.11×10^5
	27		4416.817	5.22×10^5
	6		3210.449	7.26×10^6
	6		3186.740	5.45×10^6
$z^4D^o_{5/2}$ ...	38	R (2)	4576.331	4.21×10^4
	38		4549.467	4.51×10^5
	48		5316.777	1.66×10^5
	6		3213.311	3.30×10^6
	6		3192.917	1.16×10^6
$z^4D^o_{7/2}$ ...	38	R (1, 2)	4583.829	4.85×10^5
	38		4620.513	1.91×10^4
	27		4233.167	5.87×10^5
	43		4731.439	2.31×10^5
	48		5362.864	1.94×10^5
	48		5414.089	1.11×10^5
	6		3227.75	1.69×10^7
$z^6D^o_{5/2}$ ...	UV 1	R (3)	2607.086	1.92×10^8
	UV 1	R (3)	2598.369	2.32×10^8
	40		6432.654	7.53×10^5
$z^6D^o_{7/2}$ ...	UV 1	R (3)	2585.876	1.27×10^8
	UV 1		2611.870	1.98×10^8
	40		6516.053	1.70×10^6
$z^4F^o_{3/2}$ ...	49	R (2)	5197.569	3.63×10^5
	37		4491.401	4.13×10^5
$z^4F^o_{5/2}$ ...	37	R (1, 2)	4515.337	1.86×10^5
	37		4489.185	7.72×10^4
	37		4534.166	1.08×10^5
	28		4296.567	2.36×10^5
	49		5234.620	3.49×10^5
	7		3183.115	5.92×10^6
$z^4F^o_{7/2}$ ...	37	R (1, 2)	4520.225	1.11×10^5
	37		4555.889	1.29×10^5
	37		4582.835	2.23×10^4
	28		4178.855	1.49×10^5
	49		5275.994	1.51×10^5
	49		5325.559	2.16×10^4
	7		3196.070	2.38×10^6
$z^4F^o_{9/2}$ ...	37	R (1, 2)	4629.336	1.40×10^5
	37		4666.750	4.63×10^4
	49		5316.609	2.75×10^5
	49		5425.269	2.85×10^4
$z^4P^o_{5/2}$ ...	UV 64	R (3)	2562.535	2.81×10^8
	16		3494.672	3.16×10^7
	74		6456.376	1.63×10^7

* 1. Wolnik *et al*. (1971)
2. Baschek *et al*. (1970)
3. Huber (1974)
4. Fe I also.

APPENDIX

A project was undertaken by E. Ferris and W. Whaling to measure relative transition probabilities for a number of Fe II lines seen in Seyfert galaxies. The measurements were made with a spectroscopically pure iron hollow cathode source with argon as the stimulating gas. The 5 m Paschen-Runge spectrometer at the California Institute of Technology was used. The technique used was to measure relative intensities of lines which had the same upper level as a line with a known transition probability.

The results are given in Table 4, which groups the measured lines according to the common upper level. For each line the multiplet number (Moore 1945, 1950), wavelength, and value of A s^{-1} are given. In the column labeled Reference, an R designates the line used for comparison. In the parentheses following the R is the reference for the absolute transition probability used for that line. Where more than one reference is given, the average value of A was adopted. The relative values of A should be accurate to about 5%. Individual lines have values of A which differ by up to 2 orders of magnitude from values currently being used (see, for example, Phillips 1979).

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