IUE OBSERVATIONS OF Fe II GALAXIES

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ABSTRACT

Repeated observations of the Seyfert 1 galaxies I Zw 1 and II Zw 136, which have very strong Fe II emission lines in the optical region, were made at low resolution with the IUE Satellite. The ultraviolet spectra are very similar: both are variable and show broad emission features of Fe II (especially the UV multiplets 1, 33, 60, 62 and 63) as well as the emission lines usually strong in Seyferts and quasars e.g: Lyα, Mg II, C III], C IV and N V. The data strongly support the hypothesis that the optical Fe II emission lines are primarily due to collisional excitation and that resonance fluorescence makes only a minor contribution to the excitation of these lines.

INTRODUCTION

Fe II emission lines in the optical spectra of quasars and Seyfert galaxies were first discovered in 3C273 (ref. 1) and I Zw 1 (ref. 2) and are actually present in many objects (refs. 3, 4). Usually these lines are thought to be excited by either resonance fluorescence or collisional excitation (e.g. refs. 1, 4, 9). Both mechanisms involve excitation of Fe^+ atoms from 4 even-parity levels, the ground state and 3 low-lying metastable levels, to 6 odd levels at 5 to 6 eV, and subsequent cascade to even metastable levels around 3 eV. In Fig. 1 we show an Fe^+ energy level diagram with the strongest observed optical and ultraviolet (this paper) multiplets indicated.

The excitation can be through either collisional excitation by thermal electrons or absorption of UV continuum photons in the UV resonance lines, but in both cases large optical depths in the resonance lines are required for an efficient conversion of ultraviolet to visual photons. For the case of collisional excitation we would expect both the optical and the ultraviolet lines to be in emission. For resonance fluorescence the optical lines are in emission but the ultraviolet lines could be either in absorption or emission depending on the geometrical situation. In principle, there are amply sufficient ultraviolet continuum photons available for the fluorescence mechanism; however the Fe II lines are formed in the broad line region which may cover only a small part of the continuum source and the absorption lines then must be very broad in order to intercept sufficient ultraviolet photons, requiring uncomfortably large turbulent velocities (ref. 5). Using better atomic data and more extensive model atoms it has been recently shown (refs. 5, 8) that the collisional theory can explain the observed optical Fe II lines. However attempts to observe the predicted Fe II ultraviolet emission lines in Seyfert nuclei have so far only resulted in upper limits to either absorption or emission lines (refs. 10, 12). In quasars, older work also resulted only in upper limits (e.g. ref. 13) but recently better data for several intermediate redshift objects show evidence for Fe II emission in the ultraviolet in the form of broad, low-contrast emission features (refs. 14, 15).

In this paper we present ultraviolet observations for two Seyfert galaxies, with very strong optical Fe II emission lines, which have been extensively studied in the optical. Optical studies of I Zw 1 show two redshift systems at Z = 0.0608 for low ionization lines, (ref. 16). The broad line component has relatively narrow features which greatly facilitate the study of the Fe II emission lines (refs. 2, 3-6, 16, 17). II Zw 136 has broader lines, FWHM about 2000 km sec^{-1} for I Zw 1, and a shallower spectral slope, $\alpha = 0.49$ compared with 1.33 for 1 Zw 1 (ref. 3), but in general the optical spectra of these two objects are similar (ref. 3, 4, 6). By studying these three objects simultaneously we might be able to obtain insight into the vexing problem of why some extragalactic objects show strong Fe II emission and others virtually none (refs. 4, 18). It has been suggested that Fe II emission line objects have a higher density and that the C III] 1908/C IV 1549 ratio might be lower than is normal (ref. 5). However, the available material on differences between line ratios for objects with and without Fe II optical emission is very uncertain and the separation for example of optical depth and density effects is problematical (ref. 5).

In section 2 we discuss the observations and data reduction, in section 3 we present the results for I Zw 1 and II Zw 136 and in section 4 we discuss and summarize the conclusions.

OBSERVATIONS AND DATA REDUCTION

All spectra were obtained using the IUE satellite in the low resolution mode and with the large apertures. A summary of the observations is given in Table 1. For both I Zw 1 and II Zw 136 the exposure times were determined by the strength of the strongest emission lines, Lyα and Mg II, and in the SWP images the continuum is rather faint. The last 2 SWP spectra of I Zw 1 were obtained near the end of a shift and these exposures had to be curtailed, so both are underexposed.

The SWP images were originally processed with the faulty ITF, but after subsequent correction of the ITF errors in the GPHOT image (ref. 19) we re-extracted the spectra directly from GPHOT image using improved software (ref. 19). For the LWR spectra we only reprocessed the background in order to remove particle events and image defects. An improved net spectrum was then obtained from the standard gross spectrum and the new background signal.

Only a relative wavelength scale is given, as the position of the source in the large aperture is unknown. Zero points for the absolute wavelength scales were obtained from the Lyα and Mg II emission lines in the case of I Zw 1 and II Zw 136.

Emission line strengths given in this preliminary report on these data are based on estimated continua and simply integrating the observed flux between suitable wavelength limits. The final results (ref. 20) will be based on profile fitting techniques where possible. For I Zw 1 part of the profile fitting has been done and we can accurately separate complex features like the Si II, Si III, Lyα, N V blend over $1180 < \lambda < 1250$, and estimate the strength of the individual components.

THE UV SPECTRA OF I ZW 1 AND II ZW 136

In Fig. 2 the mean long wavelength spectra of I Zw 1 and II Zw 136 are shown. For I Zw 1 rest wavelengths were calculated assuming $\lambda_o = \lambda/(1+0.0608)$, appropriate for the low ionization lines like Fe II and Mg II (ref. 7).

Comparison of the near UV spectra of Fe II Seyfert galaxies as shown in Fig. 2 with those of other Seyferts and quasars (ref. 10-12) shows two remarkable differences.

i) The Si III] λ_o 1892 intercombination line is greatly increased in strength with respect to C III] λ_o 1908. Normally Si III]/C III] is 0.1 to 0.2, in I Zw 1 Si III]/CIII] $\approx$ 0.5. Clavel (private communication) has noticed the same effect in another Seyfert galaxy with strong optical and ultraviolet Fe II emission lines.

ii) The strong "blue wing" of the Mg II line previously noticed in some medium redshift quasars (ref. 21) is also present in I Zw 1 and II Zw 136 but here clearly is not due to Mg II alone. In particular, for I Zw 1, profile fitting shows that most of the "Mg II line wing" cannot be due to Mg II at all and that Fe II UV multiplets 62 and 63 provide a good identification.

Comparison between I Zw 1 and II Zw 136 shows that the Fe II multiplets are clearly stronger in I Zw 1, as in the optical region. Only 3 multiplets UV 33, UV 62 and UV 63 can be measured easily in both objects. Multiplets UV 2, 3, 34, 35 and 36 are rather weak and blended with C II] $\lambda \sim 2326$, [Ne IV] $\lambda_o \sim 2422$ and [O II] λ_o 2470 (the Ne IV lines fall virtually on top of the fiducial at 2580 Å but inspection of the original data shows that a substantial emission line is present in both objects at $\lambda_o \sim 2422$. The red wing of multiplet UV 1 coincides with possible galactic Mg II $\lambda \sim 2798$, absorption, and in II Zw 136 the blue half of the UV 1 emission feature is absent. The latter could be a result of absorption in the object in the two resonance lines which arise from the ground state, $\lambda\lambda$ 2585 and 2600. From theoretical calculations including both fluorescence and collisional processes it appears that even in situations where collisional excitation is the dominant process, in forming the Fe II lines, some resonance fluorescence should take place (ref. 5). Some absorption could also be present in UV 2 and UV 3 and contribute to the apparent weakness of these multiplets.

In table 2 we list the observed emission line strength for both objects. In general, the emission lines do not show evidence for variability and only mean values are given; a possible exception are the weak, far UV lines of II Zw 136 and for these we give values at the two epochs. In December 1978 the weak lines in the SWP region appear to be substantially stronger than in May 1979. However the strong lines Lyα, N V and C IV do not show this effect and the "variability" could be due to errors in the estimated continuum level, which is difficult to determine in all these spectra. Even in the long wavelength spectra the results for the weak broad Fe II emission blends are sensitive to small errors in the adopted continuum. In particular, the results for UV 60 and UV 61, which in the observer's frame fall longward of 3000 Å, where the IUE sensitivity decreases rapidly, are of very low accuracy. At wavelengths λ_o < 2100 Å there exist additional as yet unidentified broad features. The C III], Si III] blend has very extended wings which could be due to Fe III emission, and the O IV], Si IV feature, $\lambda \sim 1400$, has extra emission in both the red and blue wings which appears present on all spectra. Finally, there are extensive weak emission blends for 1560 Å < λ_o < 1800 Å which cannot be explained by the presence of the He II λ1640, O III] $\sim \lambda$1666 and N III] $\sim \lambda$1750 lines. These could be due to Fe II emission from levels above 7 eV, which are strong in solar spectra, RR Tel and Nova Cygni 1978 (ref. 22-24).

We include in table 2 the total optical Fe II emission line flux and the strength of Hβ. For the strongest optical Fe II lines there is good agreement between the measurements of different observers (refs. 3, 4, 16, 17) but for the total emission line strength the weaker features have to be included and here substantial differences do exist. For I Zw 1 we used only the most recent results (ref. 17); comparison between various Hβ measurements (refs. 6, 17) shows that the older data (ref. 6) substantially overestimated the Hβ line strength. For II Zw 136 the Hβ flux (ref. 6) could also be up to 30% too high. Comparison between recent measurements of Fe II lines in both objects indicates that the most extensive set of data (ref. 6) probably still underestimates the total Fe II emission. After comparing all available data we estimate

$$F\ (\text{Fe II, optical}) \sim 10.3 \times 10^{-13}\ \text{erg cm}^{-2}\ \text{s}^{-1}$$

for II Zw 136. The optical multiplets 1, 6 and 7, which arise from the metastable a^4P level, have been excluded from the total optical Fe II emission strength. Their role is probably comparable to the Fe II ultraviolet multiplets and they have been added to the total Fe II UV flux. Combining all Fe II UV data and applying approximate corrections for blends, e.g. [O II] λ_o 2470, or multiplets not measured (UV 60 and UV 61 for II Zw 136), we obtain for the ratio of optical to ultraviolet Fe II photons: 2.8 for I Zw 1 and 2.1 for II Zw 136. The line strengths for II Zw 136 are in rough agreement with recent collisional excitation models (ref. 5), which predict comparable strength for Hβ, C III], Mg II and the ultraviolet Fe II total line strength, but with at least a factor 2 uncertainty. The highest conversion efficiency of ultraviolet to optical photons is obtained in I Zw 1 and in this object the Fe II lines appear to be considerably stronger than so far predicted; especially the optical lines. These conversion efficiencies are only rough estimates and for individual levels the conversion efficiency can differ substantially; for example for level z^6P^o the optical to UV photon ratio is $3.2 \pm^{4.4}_{1.1}$ where the errors are based on the uncertainties in the UV flux alone.

Very high column densities are indicated by these ultraviolet to optical photon ratios (ref. 9).

Towards shorter wavelengths the continuum variability increases. The December 1978 spectrum of II Zw 136 is shown in Fig. 3 and the 2 mean spectra of I Zw 1 in Fig. 4. Just as in the optical, I Zw 1 has a steeper spectral slope than II Zw 136. The C IV lines in I Zw 1 are very weak but as C III], O IV] + Si IV and N V are normal this cannot be explained by simply a lack of ionizing UV photons. There is no evidence for an intrinsic λ2200 extinction feature in either of the two Seyfert galaxies, but a weak galactic extinction feature could be present in I Zw 1 (E(B-V) < 0.03).

SUMMARY

We have observed 2 Seyfert 1 galaxies which emit strong Fe II emission lines in the optical region. They have similar UV spectra, and only differ from normal Seyferts and QSOs (refs. 10-12, 25) in the presence of easily noticable Fe II UV emission lines. In both objects the conversion of UV to optical Fe II photons seems to be comparable: for every detected UV photon there are 1 to 3 optical photons, which implies very high optical depth in the UV lines (refs. 5, 8, 9). The present data appear in good agreement with theoretical predictions based on the collisional excitation theory (refs. 5, 8, 9). The apparent absence of UV Fe II emission in earlier work is possibly due to the nature of the UV emission lines, consisting of broad blends of low contrast against the continuum which can cover the whole region between λ2300 and λ2650 (Fig. 1 and ref. 14) and the region λ > 2700 Å. Some expected UV Fe II multiplets, e.g. UV 64 a ^4D to z^4P^o, are not discovered so far; these have rest wavelengths around λ3000 and the typical observed wavelengths at λ3200 in the minimum efficiency zone between the IUE and optical domains. Again this points to the need for better observations and highlights the inherent problems in measuring these often weak, broad features. So far only one obvious difference between Fe II and normal Seyfert galaxies has been discovered: the Si III] λ 1892 line appears much stronger than is normal. It has been stressed that theoretical predictions for Fe II lines should give

self-consistent results for other strong lines, and usually Lyα, Hβ, C III], C IV and Mg II are mentioned in this respect (refs. 5, 8). The present results suggest that Si III] should be included and that a check on Fe III, which has many strong lines in this wavelength region (ref. 26) in early type stars, could be useful.

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TABLE 1

OBJECT	DATE	IUE IMAGE NR.	EXPOSURE TIME (SEC)	REMARKS
I ZW 1	2.08.78	LWR 1955	210	
I ZW 1	5.08.78	SWP 2216	200	
I ZW 1	18.08.78	SWP 2333	155	
II ZW 136	18.12.78	SWP 3637	120	
II ZW 136	27.05.79	LWR 4610	180	
II ZW 136	29.05.79	LWR 4628	180	
II ZW 136	29.05.79	SWP 5389	100	
I ZW 1	31.05.79	SWP 5411	60	underexposed
I ZW 1	2.06.79	LWR 4673	180	
I ZW 1	2.06.79	SWP 5427	60	underexposed

TABLE 2 Emission Line Intensities

line	λ_o	I ZW 1		II ZW 136		
				$F(10^{-13}$ erg cm^{-2}s^{-1}Å$^{-1})$		
Hβ	4861	3.9 ± 0.3	(1)	5.6 ± 0.5 (2)		
Fe II	optical	26.3	(1)	10? (3)		
				8.7 (2)		
				Dec 78	May 79	
Fe II	UV 60	2.4 ± 1.2				
?	290 7.6 (4)	1.1 ± 0.5			present	
Fe II	UV 61	1.4 ± 0.8				
O III	2837	0.8 ± 0.4				
Mg II	2798	6.0 ± 1.5			4.2 ± 0.6	
Fe II	UV 62] UV 63]	3.2 ± 1.6			1.0 ± 0.4	
Fe II	UV 1	1.9 ± 1.0			0.9 ± 0.6	(5)
Fe II	UV 33	1.6 ± 0.9			1.1 ± 0.3	
Fe II	UV 34 |	1.2 ± 0.5	(6)		1.5 ± 0.6	(6)
[O II]	2470 |					
[Ne IV]		present			present	
Fe II	UV 2]					
	UV 3]	<3.1 ± 1.7			2.4 ± 1.0	
	UV 35]					
	UV 36]					
C II]	2326]					
Fe II	UV 6	1.0 ± 0.5	(7)			(7)
C III]	1908 (8)]	6.0 ± 1.2			6.6 ± 0.7	
Si III]	1892]					
CIV	1549]	4.5 ± 1.5		12.1 ± 2.0	13.5 ± 2.5	
Si II	1531]					
OIV]	1402]	4.0 ± 1.0		4.8 ± 1.0	2.9 ± 0.8	
Si IV	1393]					
C II	1335	0.3 ± 0.2		1.1 ± 0.4	0.30 ± 0.15	
O I	1304	0.7 ± 0.3		3.7 ± 1.2	1.2 ± 0.4	
Si II	1263	1.5 ± 1.0		1.1 ± 0.4	1.5 ± 0.3	
N V	1240	6.0 ± 1.5	(9)	4.9 ± 2.0	3.4 ± 1.5	
Lyα	1216	16.0 ± 4.0	(9)]	32.1 ± 3.0	31.4 ± 3.0	
Si III	1206	3.1 ± 1.0	(9)]			
Si II	1192	1.5 ± 0.5	(9)]			

notes to table 2:

(1) ref. 22, (2) ref. 7, (3) see text, (4) calculated rest wavelength, comparision between I ZW 1 and II ZW 136 suggests that this is a low ionization feature (5) see text, (6) [OII] λ_o 2470 could contribute up to 30% of the total strength, (7) the reality of multiplet 6 of Fe II is questionable, (8) could include Fe III emission, (9) this four features have been separated using profile fitting methods.

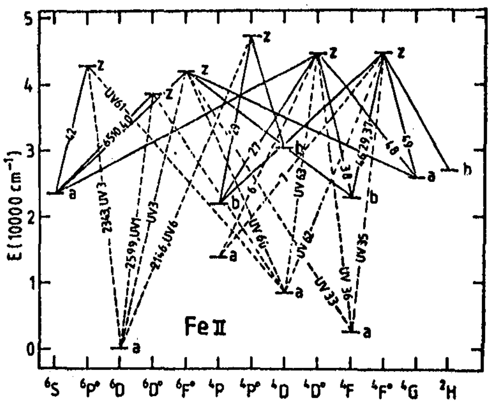

Fig. 1 Energy level diagram of Fe II with observed multiplets in the optical (———) and UV (- -) regions. For a few multiplets mean rest wavelength (Å) are shown and the multiplet numbers for most transitions are given.

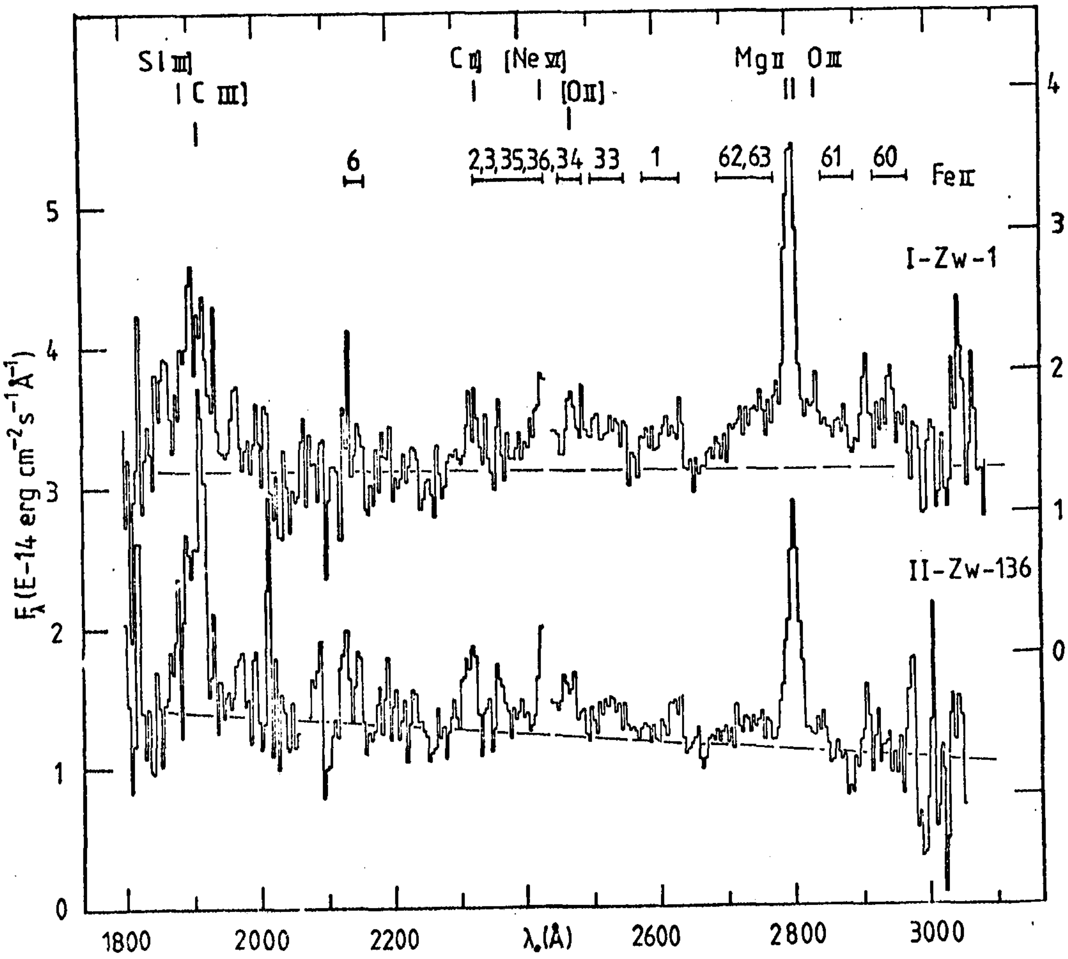

Fig. 2 Mean long wavelength spectra for I ZW 1 and II ZW 136.

I Zw 1

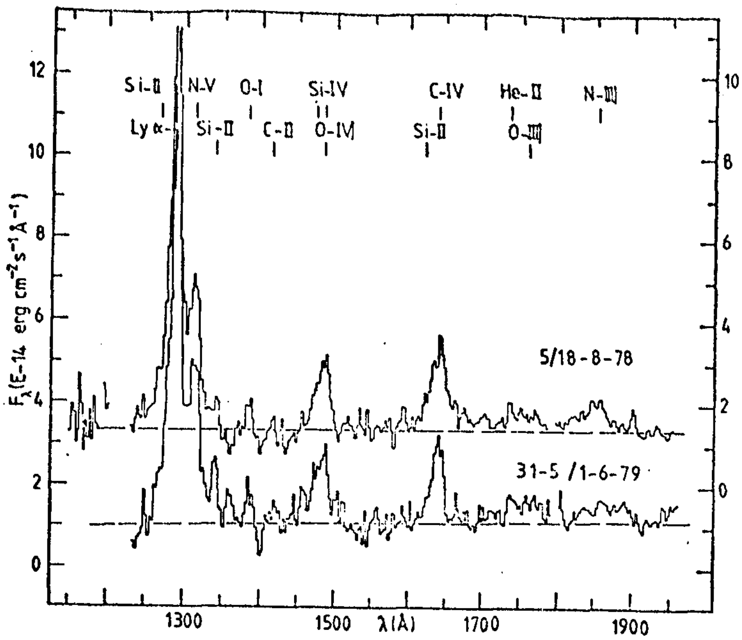

Fig. 3 Mean short wavelength spectra for I ZW 1.

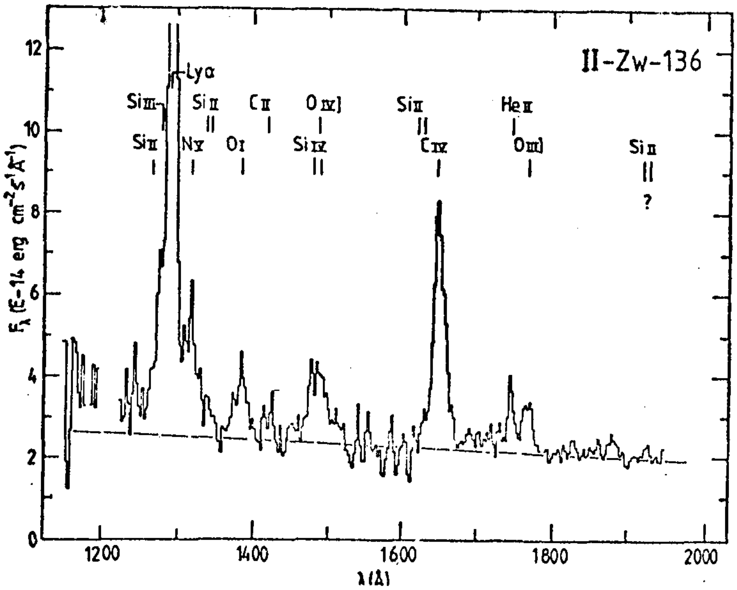

Fig. 4 One of the two short wavelength spectra for II ZW 136.