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IS OPTICAL Fe II EMISSION RELATED TO THE SOFT X-RAY PROPERTIES OF QUASARS?

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ABSTRACT

Radio-quiet quasars generally show broad, blended multiplets of Fe II emission in their optical and ultraviolet (UV) spectra. Radio-loud quasars also show UV Fe II emission, but their optical Fe II emission is generally weaker. No satisfactory theory connecting the generation of Fe II and radio emission has been found to explain this effect. A second, well-established distinction between the two classes of quasar is in their X-ray properties: radio-loud quasars are more X-ray luminous, and recent results have shown that they also have systematically flatter soft X-ray slopes. We propose that the second effect causes the first, i.e., that the primary factor controlling the optical Fe II emission is the soft X-ray spectrum. This proposition is supported by X-ray and optical data for nine quasars which shows a correlation between the soft X-ray slope and the strength of the optical Fe II emission. One of these quasars, 1803+676, is radio-quiet and yet its optical spectrum shows no evidence for Fe II emission. This quasar is also unusual in that it has a flat X-ray spectrum. This further supports our proposal that the X-ray spectrum is important in determining the relative strengths of UV and optical Fe II emission.

Subject headings: quasars — X-rays: spectra

I. INTRODUCTION

The prominent optical and ultraviolet (UV) emission lines in quasar spectra are generally believed to be produced by photoionization of the emitting gas by the "nonthermal" UV to X-ray continuum (see Ferland and Shields 1985 for a recent review). The observed emission line ratios vary by quite large factors (~ 5) from object to object. Photoionization models predict that these ratios depend primarily upon the shape of the ionizing continuum and the ionization parameter. There have been very limited studies investigating the relation between the *shape* of the ionizing continuum and emission-line strengths. This is because the extreme UV, from the Lyman limit to ~ 100 Å, is essentially unobservable due to interstellar absorption and spectral information on the soft X-ray continuum has only recently become available with the calibration of the Imaging Proportional Counter (IPC) on the *Einstein Observatory* and with *EXOSAT*. This *Letter* takes advantage of these new data.

The strongest known connection between the emission-line properties of quasars is not (apparently) related to the *ionizing* continuum. Radio-quiet quasars possess many strong, heavily blended, optical and UV Fe II [Fe II(UV)] emission lines. In radio-loud quasars Fe II(UV) emission is present, but optical Fe II [Fe II(opt)] is generally weak or absent (Peterson, Foltz, and Byard 1981; Phillips 1977; Osterbrock 1977). The observed strength of emission in the Fe II blends (both UV and optical) is often large, comparable with that of Lyα λ1215. A variety of mechanisms for generating this Fe II emission have been considered, but none of them predicts the observed link between Fe II(opt) and radio emission.

Radio-loud and radio-quiet quasars also differ in their X-ray properties. Radio-loud quasars are more luminous X-ray sources than radio-quiet quasars (see, e.g., Zamorani *et al.* 1981; Kembhavi, Feigelson, and Singh 1985). This effect is generally interpreted as being due to an additional X-ray component directly linked to the presence of radio emission, possibly via the synchrotron self-Compton process. Wilkes and Elvis (1987) have recently shown that, in addition, the soft X-ray slopes (0.1–3.5 keV) of radio-loud quasars are flatter than those of radio-quiet quasars. Given that radio-loudness is related to both the Fe II(opt) strength and the soft X-ray slope, we would expect that the two latter quantities are also related. We investigate this possibility here.

Although Fe II(opt) measurements exist in the literature for a number of quasars in the Wilkes and Elvis sample, the combination of the nonuniformity of these measurements; the different possible measurement procedures, which are rarely described; and the difficulty with finding an appropriate continuum level among the highly blended Fe II(opt) emission lines, as described by Wills (1987); conspire to make these data of dubious value for further testing the effect. We have instead measured the Fe II(opt) emission for those few quasars whose optical spectra are available to us, thus ensuring uniformity of measurement.

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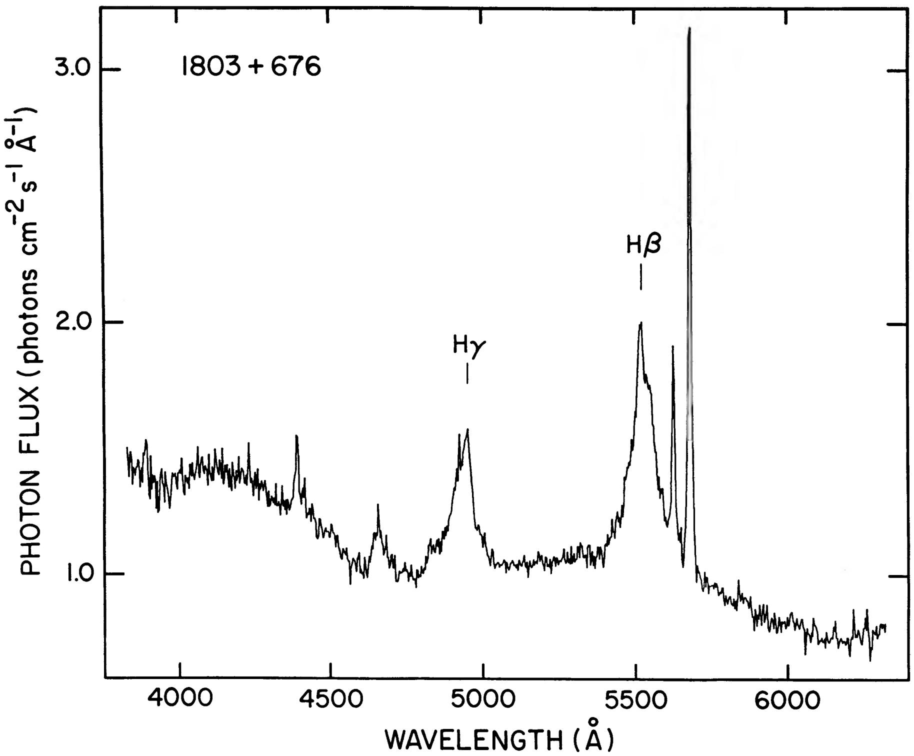

FIG. 1.—MMT spectrum of 1803+676 showing lack of obvious Fe II emission between Hβ and Hγ and longward of Hβ (z = 0.136)

II. OPTICAL DATA

Optical spectra for four of the Wilkes and Elvis quasars were obtained with the 4 m Anglo-Australian Telescope as part of a program to obtain redshifts of Parkes flat-spectrum radio sources (Wilkes *et al.* 1983; Peterson *et al.* 1979 and references therein). The Fe II λ4570 and Hβ λ4861 features[1] in these spectra were measured by fitting a power-law continuum through ~ 20–30 Å regions on either side of the feature; for Fe II: 4450 Å and 4740 Å; for Hβ: 4740 Å and 5060 Å. ([O III] λλ4959, 5007 were first removed from the red wing of Hβ.) 1803+676, also in the Wilkes and Elvis sample, was observed on the Multiple Mirror Telescope (MMT) with the MMT spectrograph and 300 lines mm^{-1} grating in 1982 September. A high signal-to-noise ratio (S/N) observation was made through 1″ × 2″.6 rectangular apertures giving ~ 5 Å resolution. A second spectrum was obtained through 5″ circular apertures to minimize the loss of blue light due to atmospheric differential refraction. The latter spectrum was flux calibrated with reference to the standard star EG 129 (Oke 1974) observed immediately beforehand using the same spectrograph setup. The high S/N (1″ × 2″.6 aperture) spectrum, normalized to the continuum of the calibrated spectrum, is shown in Figure 1. This spectrum and that of PG 1211+143, reported in Bechtold *et al.* (1987), were also measured as described above. In addition, Kriss, McHardy, and Malkan (1987) present soft X-ray slopes and optical spectra for three additional radio-quiet quasars. The X-ray data are derived from *EXOSAT* LE (low-energy) filter data and a single *EXOSAT* ME (medium-energy) data point at ~ 3 keV. (Technical details of *EXOSAT* are described in Taylor *et al.* 1981.) Their energy range is thus quite comparable to the IPC. Fe II λ4570 and Hβ strengths and widths have been extracted from the Kriss *et al.* optical spectra using the procedure described above. All the quasars have Hβ widths < 5000 km s^{-1}. Based upon the results of Wills (1987), we do not expect line blending in the Fe II(opt) multiplets to significantly affect the measured Fe II strength in these objects, although we note that our method of measurement is different. For all nine quasars the X-ray slopes, the observed equivalent widths of Fe II λ4570, its strength relative to Hβ λ4861 and the observed full width at half-maximum (FWHM) of Hβ are given in Table 1 in order of increasing X-ray slope. In Figure 2 the Fe II equivalent widths are plotted as a function of the soft X-ray slope. The quasar redshifts are low ($\lesssim$ 0.3) so that conversion to rest frame values is unnecessary.

[1] Hβ measurements are reported in Wilkes (1986). The line was remeasured here to ensure consistency with the other quasars in this paper. Differences between these and the earlier measurements are within the expected errors (~ 10% for FWHM).

III. DISCUSSION

Although this is a crude measurement of Fe II(opt), with no allowance made for the presence of He II λ4648 emission or differing emission line widths, there is a clear trend of increasing Fe II(opt) strength with steepening of the soft X-ray slope (Fig. 2). The correlation coefficient is 0.894 (99.8% significance). We note that Remillard and Schwartz (1987*a*, *b*) have found a similar relation from optical spectroscopy and *EXOSAT* spectra of hard X-ray selected quasars from the *HEAO 1* A-3 survey.

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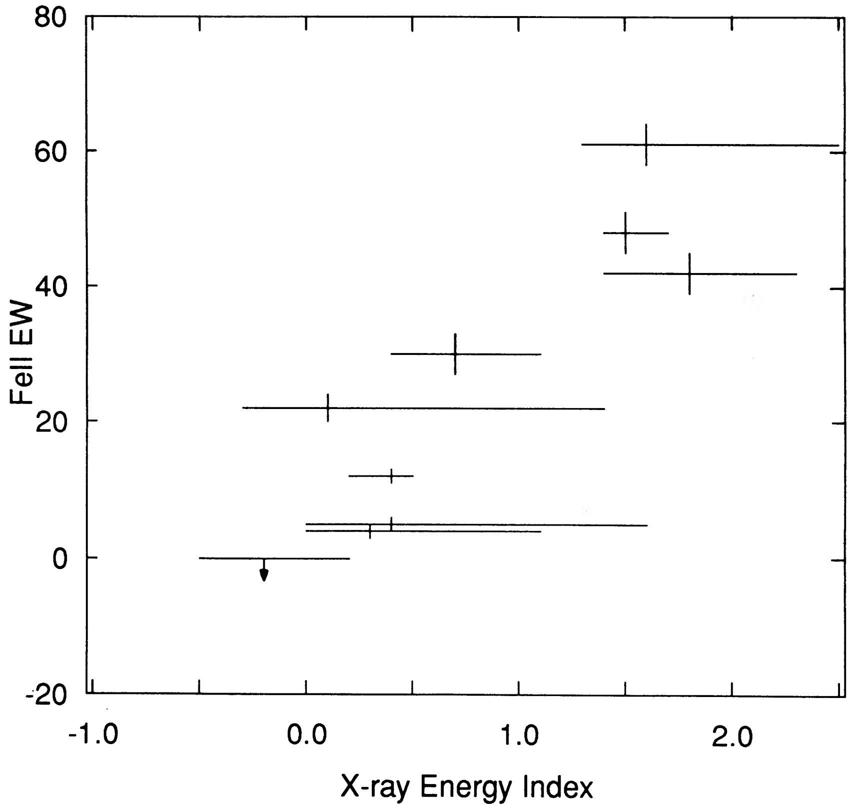

FIG. 2.—Observed equivalent width (in Å) of the Fe II λ4570 blend as a function of soft X-ray slope. EW width errors are estimated at ~ 10%; X-ray errors are 90% confidence limits for two parameters.

TABLE 1
X-RAY SLOPES AND OPTICAL Fe II STRENGTHS[a] OF QUASAR

Quasar	X-Ray Energy Index[b]	Fe II EW(Å)[c]	Fe II:Hβ	Hβ:FWHM[d]
1803+676	$-0.2^{+0.4}_{-0.3}$	< 0.2	< 0.005	3800
0312−770	$0.1^{+1.3}_{-0.4}$	22	0.21	3340
1146−037	$0.3^{+0.8}_{-0.3}$	4	0.05	4300
III Zw 2	$0.4^{+1.2}_{-0.4}$	5	0.06	4700
3C 273	$0.4^{+0.1}_{-0.2}$	12	0.2	4200
PG 0923+129	$0.7^{+0.4}_{-0.3}$	30	0.69	1840
PG 1229+204......	$1.5^{+0.2}_{-0.1}$	48	0.67	3170
PG 0844+349......	$1.6^{+0.9}_{-0.3}$	61	0.97	2480
PG 1211+143......	$1.8^{+0.5}_{-0.4}$	42	0.65	1620

[a] Measured between Hβ and Hγ, as described in the text.
[b] 90%, two-parameter error, from Wilkes and Elvis 1987 or Kriss *et al.* 1987.
[c] In observed frame.
[d] km s^{-1} in observed frame.

Since radio-loudness and X-ray slope are well correlated, it is intrinsically difficult to determine which quantity is fundamentally related to the optical Fe II(opt) emission. The nine crude measurements presented here are insufficient and there is no sample of quasars available for which both X-ray and careful, systematic Fe II(opt) measurements have been made which would allow a principle component analysis. A clear distinction could be made, for individual quasars at least, with Fe II(opt) measurements for either radio-loud quasars with steep soft X-ray slopes or conversely radio-quiet quasars with flat soft X-ray slopes. There is one such crucial object in the Wilkes and Elvis (1987) sample: 1803+676 (KAZ 102; Kazaryan, Carswell, and Khachikyan 1974).

1803+676 is a radio-quiet quasar (Hutchings and Gower 1985), yet it has a best fit soft X-ray slope, α_E, of −0.2 ($F_\nu \propto \nu^{-\alpha_E}$), flatter than the flattest radio-loud quasar in the Wilkes and Elvis sample. If weak radio-emission implies strong Fe II(opt) emission then 1803+676 should show strong Fe II(opt). If instead flat X-ray slopes are associated with weaker Fe II(opt) lines then these lines should be weak in

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1803 + 676. Our spectrum (Fig. 1) shows no apparent Fe II(opt) emission. In particular Fe II λ4570, which generally appears as a broad feature between Hβ λ4861 and Hγ λ4340, is not seen (e.g., compare with spectra in Peterson, Foltz, and Byard 1981). Fe II λλ4924, 5018 are also not apparent, and a possible feature at Fe II λ5169 is very weak. While we do not claim high photometric accuracy for the spectrum in Figure 1, it is sufficient to show that the excess emission at the blue end is consistent with Balmer continuum emission, generally a broad (~ 800 Å) feature spanning the Balmer limit at 3647 Å. The continuum drops considerably longward of Hβ; while this is most likely due to poor flux calibration, we cannot rule out the possibility that Fe II emission is present between Hβ and Hγ at exactly the right level to produce a smooth flat continuum at a higher level. However, this seems rather contrived particularly since the associated Fe II emission lines longward of [O III] are absent. We thus conclude that 1803 + 676 has weak or no Fe II(opt) emission. As noted above this is unusual for a radio-quiet quasar and suggests that the soft X-ray slope is more important than the radio emission in determining the strength of the optical Fe II(opt) emission.

Theoretical arguments also lead us in this direction. The emitting clouds in the broad emission line region (BELR) of quasars are generally believed to be photoionized by continuum emission from a powerful, nonthermal central source. The shape and normalization of the incident X-ray spectrum is crucial in determining the ionization balance in these clouds (Netzer 1987). With the discovery of strong ultraviolet Fe II emission lines, collisional excitation was concluded to dominate the Fe II line production (Wills *et al.* 1980; Collin-Souffrin *et al.* 1980; Kwan and Krolik 1981). X-rays penetrate deep into the clouds creating a warm, partially ionized zone at high optical depths where low ionization lines, such as Fe II emission, are generated (Kwan and Krolik 1981). The ratio Fe II(opt)/Fe II(UV) increases with the optical depth in the Fe II(UV) resonance lines (Netzer and Wills 1983). Thus both the total strength of the Fe II emission and the ratio Fe II(UV)/Fe II(opt) are expected to be strongly related to the X-ray flux incident upon the BELR clouds. On the other hand, no obvious link is expected between Fe II(opt) and a quasar's radio emission.

Based upon our observational results and these theoretical considerations, we suggest that the Fe II(opt) strength is fundamentally related to the slope in the soft X-ray region (0.1–3.5 keV). The Fe II(opt)/radio-loudness relation is then a secondary relation resulting from the primary relation between the soft X-ray slope and radio-loudness.

It should be noted that, while an X-ray/Fe II(opt) relation is expected, the sense of the relation predicted by most current photoionization models of the emitting gas is opposite to that we observe (Krolik 1987). In these models Fe II does not become a dominant coolant until high column densities 10^{22}–10^{23} atoms cm^{-3}; in this region the gas is heated mainly by photons at ≥ 1 keV. Since the more efficient soft photons are then absent, the overall Fe II emission will be higher for those quasars with stronger hard X-ray flux in the IPC energy band. Thus radio-loud quasars are expected to have stronger Fe II(opt) emission, i.e., since they are both more luminous and have flatter slopes. This is opposite to the trend suggested by the observations and presents an interesting theoretical problem. Modification of current photoionization models to include more realistic X-ray continua for the two classes of quasars are essential to further understanding this situation.

It is also possible that these models are simply inadequate in their prediction of the Fe II strength. They have proved unable to reproduce the high observed Fe II strengths without invoking at least one additional component with lower ionization parameter and higher density (Collin-Souffrin, Dumont, and Tully 1982; Wills, Netzer, and Wills 1985; Joly 1987; Wills 1987). Successful modeling of the Fe II production may give a different prediction for the X-ray/Fe II(opt) relation.

Other possible explanations of the Fe II(opt)/radio-loudness relation have been suggested. For example, Wills and Browne (1986) and Miley and Miller (1979) have shown that compact radio quasars have significantly narrower emission lines than extended radio quasars. The more severe blending of the Fe II emission lines which occurs for quasars with broader emission lines hides the underlying continuum reducing the apparent Fe II strength and causing an apparent difference between its strength in compact and extended radio quasars (Wills, Netzer, and Wills 1985; Wills 1987). They emphasize that accurate measurements of Fe II emission-line strength can only be obtained via detailed modeling of the observed spectrum to take into account this line blending (Wills, Netzer, and Wills 1985). This procedure has not yet been applied to radio-quiet quasars in order to determine whether the radio-loud/radio-quiet Fe II(opt) discrepancy could also be explained by this effect. However, radio-quiet and compact radio-loud quasars generally have similar line widths while the discrepancy between their Fe II(opt) strengths appears to be much more marked than for the two classes of radio-loud quasars. For example, the sample of Bergeron and Kunth (1984) shows no significant difference between the Fe II(opt) strengths for compact and extended radio-loud quasars while that for radio-loud and radio-quiet is very strong (see their Fig. 9). Thus, although confirmation must await more detailed study, it seems unlikely that line blending alone is the cause of the discrepancy (Osterbrock 1985).

In our small sample we cannot rule out the possibility that the line width is affecting our Fe II λ4570 measurements. In Table 1 it is apparent that those quasars with narrow lines and strong Fe II are also those with steep X-ray slopes. The correlation between Fe II(opt) and line width does not appear as strong as that with X-ray slope, but we cannot confirm this suspicion with our small dataset. If the line width is causing our Fe II(opt)/α_E relation, then there must be a relation between line width and α_E, which in turn must be explained.

Finally, physical mechanisms connecting Fe II and radio emission have been suggested by Ferland and Mushotzky (1984) and by Boyd and Ferland (1987). The former suggests that the relativistic gas which produces the synchrotron radio emission is mixed with the gas in BELR. The interaction of cosmic-ray electrons with the BELR gas heats the neutral gas sufficiently to quench the Fe II emission. The latter paper uses γ-rays to destroy the heavy elements, including Fe in the BELR gas. A Fe II/radio-loudness connection follows if

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radio-loud quasars are also γ-ray–loud, a logical extension of their X-ray loudness. Although both models predict the observed relation between optical Fe II(opt) and radio emission, they cannot explain the observed lack of a similar relation for UV Fe II (Bergeron and Kunth 1984).

IV. CONCLUSIONS

Based on nine quasars we suggest that the soft X-ray slope is related to the Fe II(opt) emission. The well-known statistical link between Fe II(opt) and radio emission of quasars and active galactic nuclei is then secondary, a result of the strong link between the soft X-ray and radio emission. A link with the ionizing continuum seems physically more reasonable than one with the radio luminosity.

More generally, this result shows that soft X-ray spectra provide a new tool for understanding quasar emission lines and for testing photoionization models for the BELR. It is clear that careful measurements of the optical emission lines for *individual quasars with well-determined X-ray spectra* are essential to a systematic study. Since the known Fe II(opt)/radio loudness relation possesses a good deal of scatter, a large sample of radio-quiet and radio-loud quasars with X-ray slopes must be studied to understand these and any additional correlations fully. Should photoionization models prove unable to reproduce the observations, we will be forced to conclude that there is a more important difference between flat X-ray spectrum (radio-loud) and steep X-ray spectrum (radio-quiet) quasars which determines the relative strength of optical and UV Fe II emission.

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