THE ASTROPHYSICAL JOURNAL, 382:121–124, 1991 November 20

Fe II EMISSION AND ANISOTROPY IN BROAD-LINE REGIONS

WEI ZHENG AND WILLIAM C. KEEL
Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487-0324
Received 1990 March 27; accepted 1991 May 23

ABSTRACT

We examine the relative strength of Fe II λ4570 in 138 active galactic nuclei in relation to the line width of Hβ. For objects with FWHM (Hβ) greater than 6000 km s^{-1}, the mean Fe II λ4570/Hβ intensity ratio is 0.21, less than half of that in the other objects. The result confirms a general tendency, seen in earlier work on smaller samples, that strong optical Fe II emission is not found in objects showing very broad emission lines. In particular, all five objects with exceptionally broad and flat profiles, such as Arp 102B, have weak or absent Fe II emission. We have verified that this effect is not an artifact of blending of the Fe II multiplets or of underestimation of the Hβ line width due to blending with Fe II features.

The anticorrelation between the Fe II λ4570 strength and line width may be interpreted as an effect of source orientation. The Fe II region is either highly anisotropic or is not coextensive with the conventional broad-line region such as the assumed disk-shaped low-ionization zone. This is consistent with the Fe II region being associated with a small-scale jet and embedded in a thick torus, and hence being visible only in nearly face-on positions.

Subject heading: galaxies: nuclei

1. INTRODUCTION

Accretion is widely believed to be the most likely power source of luminous active nuclei (see review by Begelman 1985). The large velocity widths characteristic of the broad-line regions of these objects are usually interpreted as gravitationally driven, but it is far from clear that ordered rotational motion plays an important role in the observed line profiles (Mathews 1982). This issue has been given renewed currency by the observation of remarkable structure in line profiles of several broad-line radio galaxies. Oke (1987) and Pérez et al. (1988) suggest that the observed broad Balmer lines in 3C 390.3 can be fitted with a double-horn profile produced by an accretion disk. Chen, Halpern, & Filippenko (1989) present a detailed fit to the Hα profile of Arp 102B and suggest that its broad profile with a blue hump is the signature of an accretion disk. The applicability of such an interpretation is of extraordinary interest, since it suggests that some active galactic nuclei (AGNs) have directly observable accretion disks. Given a central mass of $10^7\ M_\odot$, the size of a typical broad-line region for Seyfert galaxies as determined from the studies of variability is on the order of several thousand Schwarzschild radii. The rotational velocity at such a radius is sufficiently large to produce the observed broad-line widths.

There are also theoretical reasons for believing that the strong Fe II emission seen in many broad-line AGN might be associated with such accretion disks. It has long been argued (Bergeron & Kunth 1980; Collin-Souffrin et al. 1986; Joly 1987; Collin-Souffrin, Hameury, & Joly 1988) that the optical Fe II multiplets are too strong in many AGN to admit simple photoionization schemes, and that this emission is enhanced in high-density ($>10^{11}$ cm^{-3}) clouds which are likely to exist in the outskirts of an accretion disk. Alternately, Fe II emission may originate in clouds of very high optical depth (column density $>10^{24}$ cm^{-2}; Ferland & Persson 1989) even if the density is only on the order of 10^9 cm^{-3}. In the first case, one might expect the very broad line AGN to produce especially strong optical Fe II emission because (1) their peculiar profiles, often with double humps, probably make them the best candidates for emission from accretion disks and (2) the large rotational velocities implied by their extreme permitted–line widths would require an unusually compact line-emitting region and higher than normal density associated with a disk for the Fe II emission.

However, there have been signs that objects with very broad lines actually have weak or absent optical Fe II emission. Grandi & Osterbrock (1978), based on their sample of 35 radio galaxies, find that these broad-line galaxies show weak Fe II, large [O III]/Hβ ratios, and steep Balmer decrements. Zheng & O'Brien (1990) find, in a sample of 33 QSOs which are X-ray sources, that the relative strength of optical Fe II decreases with the line width of Hβ. The trend becomes apparent when the line width is broader than 5000 km s^{-1}. This violation of straightforward predictions has prompted us to perform a statistical study using a larger sample than previously available. We consider QSOs, Seyfert galaxies, and radio galaxies together here, motivated by the evidence in favor of a "unified scheme" connecting these objects by orientation-dependent visibility of some components (Scheuer & Readhead 1979; Orr & Browne 1982; Barthel 1989; Urry, Maraschi, & Phinney 1991).

2. RESULTS

Most of the data we have used are from statistical reports in the literature (Osterbrock 1977; Grandi & Osterbrock 1978; Grandi 1981; Bergeron & Kunth 1984; Blumenthal, Keel, & Miller 1982; Stephens 1989). Some individual objects with very strong Fe II or very broad widths carry appreciable statistical weight; therefore their data are collected from individual studies: Mrk 231 is from Boksenberg et al. (1977); 0759+650 from Lawrence et al. (1988); PHL 1092 from Bergeron & Kunth (1980); 3C 382 and 3C 390.3 from Osterbrock, Koski, & Phillips (1975); Arp 102B from Stauffer, Schild, & Keel (1983), PHL 909 from Zheng & Burbidge (1988), 1850−782 from Lìpari, Macchetto, & Golombek (1991), and 3C 351 from new

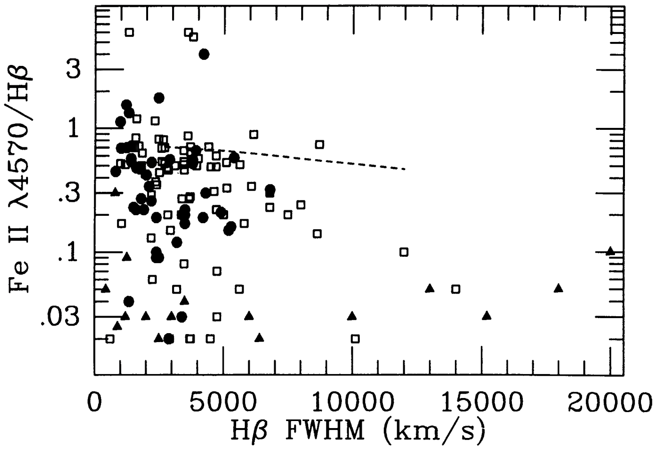

FIG. 1.—Fe II λ4570 ratio to Hβ vs. Hβ FWHM. *Open squares:* QSOs; *triangles:* radio galaxies; *solid circles:* Seyfert galaxies. Dashed line shows effect of simulated broadening.

far-red (Hα) data obtained with the 4.2 m William Herschel Telescope (WHT) on La Palma. Unless indicated otherwise, the Fe II emission referred to is that of optical Fe II near 4570 Å.

Figure 1 shows Fe II λ4570 to Hβ intensity ratio versus full width at half-maximum (FWHM) of Hβ. Typical errors are estimated as 20% for Fe II λ4570/Hβ ratio and 500 km s^{-1} for Hβ width. For 3C 351 the Hα FWHM is used, since the broad component of Hβ is too weak for accurate measurement (see Netzer, Wills, & Wills 1982). The FWHM may not be well-defined if a profile consists of both strong narrow and broad profiles (the typical "Seyfert 1.5" case). In a few objects, the narrow component is so strong that at the half-maximum level the profile is still narrow; we classify these objects as broad-line objects, because the Fe II emission is likely to originate in a broad-line region, and use the FWHM of the broad component as best we can estimate it. The Fe II λ4570/Hβ ratio in these rare objects is not large, so our statistical arguments would not be altered even if they are classified according to their narrow components. There are several cases where the Balmer profiles are especially flat, so that the FWHM is more than 60% of the full width at zero intensity. They have sometimes been considered as the best candidates for directly observable accretion disks in AGNs. Therefore, the strength of Fe II in these objects is of special interest. Excluding the four objects with extraordinarily large Fe II λ4570/Hβ ratios, the mean value of Fe II λ4570/Hβ is 0.37 for the whole AGN sample. The standard deviation is 0.32.

For several objects with very broad profiles, we have used archival spectroscopic data to carefully determine the continuum level by fitting with three to four wavelength bins. We do find probable weak Fe II emission for PHL 909. The level of "featureless continuum" within 400 Å on both sides of Hβ is slightly higher than in other wavelength regions, and we interpret this as the optical Fe II emission around 4570 and 5200 Å. For 3C 390.3, weak Fe II emission was reported in the object's high state (Netzer 1982) but the feature is almost undetectable in more recent observations.

3. DISCUSSION

There are significant measurement effects which can lead to large uncertainties in the Fe II strength. The Fe II measurement itself is not consistently defined: different kinds of continuum fitting are used by various authors. In several comprehensive studies of Fe II emission, such as Grandi (1981) and Wills, Netzer, & Wills 1985), the continuum is fitted according the overall shape over a wide range of wavelength (larger than 3000 Å). Some other studies appear to adopt a simple continuum setting on either side of the (apparent limits of the) λ4570 and λ5200 multiplets. If a nearby region believed to be free of line emission is used, the Fe II strength could be significantly smaller. Therefore the data used in this study suffer from the lack of clear definition as well as from personal bias. Another source of uncertainty is sensitivity to line widths. As Wills (1988) indicates, in cases with broad lines the continuum level tends to be overestimated due to blending of the many optical Fe II multiplets and, consequently, the Fe II flux measured with respect to her "pseudocontinuum" would be underestimated. Zheng & O'brien (1990) test their sample and find that this effect indeed leads to underestimate the Fe II emission by up to 30% when lines are broader than 5000 km s^{-1}, but would not account for the general weakness associated with the broad Balmer lines. In fact, we are able to detect the weak optical Fe II emission in PHL 909 despite its very broad Balmer line widths. This suggests that the weakness or absence of Fe II emission in objects with very broad lines such as Arp 102B is intrinsic.

We have checked our results for this effect and a related one—possible underestimation of the Hβ FWHM due to overestimation of the true continuum level in the presence of broad Fe II emission. This is done by convolving a "typical" object's spectrum (3C 48) to known line width and measuring the resulting broadened spectrum just as is typically done for estimates of Hβ line width and Fe II λ4570/Hβ. The results of this excercise are shown as the dashed line in Figure 1. While we do see both of these kinds of measurement artifacts, they are insufficient to account for the complete lack of known objects with large line width and strong Fe II. We know of no other bias that would act against recognition of Fe II in objects with large broad-line widths.

The strength of Fe II λ4570 has been shown to correlate well with the total strength of all multiplets of optical Fe II emission. Collin-Souffrin et al. (1986) investigate this relation from published data and find that Fe II λ4570, mainly multiplets 37 and 38, accounts for about 25% of the total Fe II emission. Thus, our result suggests a tendency that strong Fe II emission is not seen in very broad line objects.

Although many details remain unclear, the Fe II emission is believed to originate from transitions to metastable levels. Its strength would not be significant unless radiative transfer hampers the transitions leading to UV Fe II emission in the condition of high density and/or high opacity. Model calculations (Wills et al. 1985; Collin-Souffrin et al. 1986; Ferland & Persson 1989) have shown that high opacity (column density $\gg 10^{23}$ cm^{-2}) is a critical factor. Although the density of a typical broad-line region is sufficiently high to produce Fe II emission, a very high density ($> 10^{11}$ cm^{-3}) would certainly boost the Fe II emission. In a partially ionized zone, the emissivity is determined by the collisional excitation and is therefore highly sensitive to temperature. It is suggested (Joly 1991) that additional heating factors such as shock waves would increase the Fe II strength.

In Table 1, we summarize the relative Fe II intensity for AGNs of different Hβ line widths. The samples are divided by their Hβ line widths into three groups. It is clear that the

TABLE 1

Fe II STRENGTH IN ACTIVE GALACTIC NUCLEI

GROUP	NUMBER OF OBJECTS	Fe II λ4570/Hβ			
		<0.1	0.1–0.4	>0.4	Median[a]
Seyfert galaxies	45	16%	42%	42%	0.41
QSOs	79	16%	29%	55%	0.40
Radio galaxies	14	86%	14%	0%	0.06
Narrow-line objects (FWHM < 2000 km s^{-1})	35	17%	17%	66%	0.52
Medium-line objects (FWHM 2000–6000 km s^{-1})	85	22%	34%	44%	0.35
Broad-line objects (FWHM > 6000 km s^{-1})	18	39%	50%	11%	0.21

[a] Exclude objects with Fe II λ4570/Hβ greater than 2.

objects with narrower (BLR) lines show a significant amount of Fe II emission. For those with Hβ FWHM less than 6000 km s^{-1}, the average Fe II λ4570/Hβ ratio is 0.57, more than twice as high as that derived from conventional photoionization models, which give typically 0.2 (Kwan & Krolik 1981). This further confirms the claim by Wills et al. (1985) and Collin-Souffrin et al. (1986) that there is an excess of Fe II emission by at least a factor of 2. However, we find that there is no enhancement of Fe II emission in the very broad line objects such as would suggest a high-density, high-opacity region associated with accretion disks.

In Table 1 we also present the mean values grouped by classification as radio galaxies, Seyfert galaxies, and QSOs. There is no significant difference of Fe II strength between Seyfert galaxies and QSOs, perhaps since many published spectra are of Fe II–strong QSOs. However, by the same token, this suggests that the weakness of Fe II emission for broad-line objects is not associated solely with radio galaxies and QSOs. Since data are from different sources the distinction between the groups are based mainly on luminosity and is not strictly defined. For example, Stephens (1989) defines her samples by luminosity and some general characteristics, so the sample of Seyfert galaxies include objects with redshift of up to 0.4.

The above analysis suggests that it is the *narrow-line* objects which often show strong Fe II emission. The broad-line region geometry probably plays an important role in this relation, and the radio morphology may also be linked. Miley & Miller (1979) and Boroson & Oke (1984) have suggested that quasars associated with weak core, double-lobe, steep spectrum radio sources tend to have weaker Fe II emission. This can be interpreted as objects seen edge-on with respect to a central disk, whose orientation influences that of the radio source. A relation between line widths and radio and optical properties has also been noted (Wills & Browne 1986) which implies some geometric effect in the visibility of these features. If the broad-line region has a disklike form, very broad profiles are likely to be seen in disks viewed edge-on. The anticorrelation discussed in this paper may presumably be associated with an orientation effect, i.e., Fe II emission is apparently weak in an edge-on position regardless of intrinsic Fe II strength.

We divide the subsample of QSOs with narrower line width (FWHM < 4000 km s^{-1}) into three groups: radio-quiet, core-dominated (core radio emission greater than extended radio emission), and lobe-dominated sources. The data on radio emission are from Wills & Browne (1986). Since the line widths of these elected objects are similar, orientation effects should be reduced. The radio-quiet group, excluding the three super-strong Fe II–emitters (Fe II λ4570/Hβ > 2), has an average Fe II λ4570/Hβ ratio of 0.50, a value shared by the core-dominated radio sources. The lobe-dominated sources have a low average value of 0.19. We caution that this trend is only statistical because exceptions do exist in individual objects. The results are consistent with (1) Bergeron & Kunth (1980) about the excessive strength of Fe II emission in radio-quiet objects, and (2) Joly (1991) that the Fe II emission in objects with high radio core luminosity is stronger than that in lobe-dominated radio sources. At least the latter link is likely to be an orientation effect, because it is commonly believed that core-dominated radio sources are viewed face-on.

The Fe II–emitting region would then have to be so anisotropic that it would not be seen when the disk is edge-on. This assumption is supported by Bergeron & Kunth in that Fe II strength is not well-correlated with other low-ionization lines such as Mg II. Their results and ours suggest that the Fe II–forming region is distinct from the conventional broad-line region which, according to the finding of Wills & Browne, may take a disk shape in many radio sources. We follow Norman & Miley (1984) and postulate that this region is along the polar radio jet, embedded in a thick torus. It is also assumed that the major part of the other emission such as Hβ and Mg II originates in a conventional broad-line region, and thus these lines are not considerably affected by such obscuration. Such a thick torus is suggested by Antonucci & Miller (1985) to account for the differences between type 1 and type 2 Seyfert galaxies. They use spectropolarimetry to reveal the weak, otherwise hidden broad emission lines (FWHM ~ 7500 km s^{-1}) and Fe II features in NGC 1068. In Figure 5 of their paper they draw a possible geometrical configuration in which the broad-line region is surrounded by a geometrically and optically thick disk. Only photons traveling out along the polar direction can scatter into the line of sight. The existence of "hidden" Fe II emission is particularly intriguing because it indeed implies a very large optical depth for the clouds in the funnel.

As Norman & Miley (1984) suggest, the Fe II–emitting region may be produced by shocks along the radio jet. If so, in a face-on position the Fe II emission is stronger, and the emission lines have narrower widths. In this regard, it is important to know whether the correlation between far-IR spectral shape and Fe II emission proposed by Low et al. (1989) actually holds, since this might imply that Fe II is related to an orientation-independent property and thus that true differences in the BLR structure are important in the relative strength of Fe II. A larger sample of *IRAS*–selected AGNs from the work of de Grijp et al. (1991) shows no strong effect in this direction; further work is clearly needed on this issue. In some narrow-line objects individual Fe II features can be seen. A comparison of the Fe II and Hβ profile may test the hypothetical geometry: their profiles may be different if Hβ is mainly formed in a disk and Fe II is formed in a polar jet. We note that most of the objects with very broad line widths are radio galaxies. The inclination effect may also link them with other radio galaxies and quasars (Barthel 1989).

4. SUMMARY

We have found no evidence of enhancement of optical Fe II emission from objects with very broad emission lines, such as would be expected if this emission arises in the outer parts of accretion disks. This suggests that the Fe II–emitting region is not in a shape of disk.

The statistical envelope connecting Fe II strengths and line widths holds for all AGNs, suggesting a general anisotropic geometry for the Fe II–emitting region and one somewhat different from that emitting the broad permitted lines. In radio sources, the Fe II emission may be enhanced along the polar jet, but only visible in a near face-on position, probably because of the obscuration by a thick torus.

We acknowledge support by EPSCoR grant RII-8996152. Steven Grandi is thanked for allowing us to use his high S/N data on 3C 48 for a broadening simulation. The WHT is operated at the Observatorio del Roque de los Muchachos by the Royal Greenwich Observatory, on behalf of the UK SERC.

REFERENCES

Antonucci, R. R. J., & Miller, J. S. 1985, ApJ, 297, 621
Barthel, P. D. 1989, ApJ, 336, 606
Begelman, M. C. 1985, in Astrophysics of Active Galaxies and Quasi-Stellar Objects, ed. J. S. Miller (Mill Valley, CA: University Sciences), 411
Bergeron, J., & Kunth, D. 1980, A&A, 85, L11
———. 1984, MNRAS, 207, 263
Blumenthal, G. R., Keel, W. C., & Miller, J. S. 1982, ApJ, 257, 499
Boksenberg, A., Carswell, R. F., Allen, D. A., Fosbury, R. A. E., Penston, M. V., & Sargent, W. L. W. 1977, MNRAS, 178, 451
Boroson, T. A., & Oke, J. B. 1984, ApJ, 281, 535
Chen, K., Halpern, J. P., & Filippenko, A. V. 1989, ApJ, 339, 742
Collin-Souffrin, S., Dumont, S., Joly, M., & Péquignot, D. 1986, A&A, 166, 27
Collin-Souffrin, S., Hameury, J.-M., & Joly, M. 1988, A&A, 205, 19
de Grijp, M. H. K., Miley, G. K., Keel, W. C., Goudfrooij, P., & Lub, J. 1991, A&A, in press
Ferland, G. J., & Persson, S. E. 1989, ApJ, 347, 656
Gaskell, C. M. 1983, in Quasars and Gravitational Lenses, Proc. 24th Liège Int. Ap. Coll. (Liège: Institut d'Astrophysique, Université de Liège), 473
Grandi, S. A. 1981, ApJ, 251, 451
Grandi, S. A., & Osterbrock, D. E. 1978, ApJ, 220, 783
Joly, M. 1987, A&A, 184, 33
———. 1991, A&A, 242, 49
Kwan, J., & Krolik, J. H. 1981, ApJ, 250, 478
Lawrence, A., et al. 1988, MNRAS, 235, 261
Lipari, S., Macchetto, F. D., & Golombek, D. 1991, ApJ, 366, L65
Low, F. J., Cutri, R., Kleinmann, S. G., & Huchra, J. 1989, ApJ, 340, L1
Mathews, W. G. 1982, ApJ, 258, 425
Miley, G. K., & Miller, J. S. 1979, ApJ, 228, L55
Miller, J. S., & Peterson, B. M. 1990, ApJ, 361, 98
Netzer, H. 1982, MNRAS, 198, 589
———. 1988, in IAU Symposium 134, Active Galactic Nuclei, ed. D. E. Osterbrock & J. S. Miller (Dordrecht: Kluwer), 69
Netzer, H., Wills, B. J., & Wills, D. 1982, ApJ, 254, 489
Norman, C., & Miley, G. 1984, A&A, 141, 85
Oke, J. B. 1987, in Superluminal Radio Sources, ed. J. A. Zensus & T. J. Pearson (Cambridge: Cambridge Univ. Press), 267
Orr, M. J. L., & Browne, I. W. A. 1982, MNRAS, 200, 1067
Osterbrock, D. E. 1977, ApJ, 215, 733
Osterbrock, D. E., Koski, A. T., & Phillips, M. M. 1975, ApJ, 197, L41
Pérez, E., Penston, M. V., Tadhunter, C., Mediavilla, E., & Moles, M. 1988, MNRAS, 230, 353
Scheuer, P. A. G., & Readhead, A. C. S. 1979, Nature, 277, 182
Stauffer, J., Schild, R., & Keel, W. 1983, ApJ, 270, 465
Stephenson, S. A. 1989, AJ, 97, 10
Urry, C. M., Maraschi, L., & Phinney, E. S. 1991, Comm. Ap., 15, 111
Wills, B. J. 1982, in IAU Symposium 97, Extragalactic Radio Sources, ed. D. S. Heeschen & C. M. Wade (Dordrecht: Reidel), 373
———. 1988, in Physics of Formation of Fe II Lines Outside LTE, ed. R. Viotti, A. Vittani, & M. Friedjung (Dordrecht: Reidel), 161
Wills, B. J., & Browne, I. W. A. 1986, ApJ, 302, 56
Wills, B. J., Netzer, H., & Wills, D. 1985, ApJ, 288, 94
Zheng, W., Binette, L., & Sulentic, J. W. 1990, ApJ, 365, 115
Zheng, W., & Burbidge, E. M. 1988, ApJ, 328, 175
Zheng, W., & O'Brien, P. T. 1990, ApJ, 353, 433