THE ASTROPHYSICAL JOURNAL, 416:150–156, 1993 October 10


# RADIO AND NEAR-INFRARED [Fe II] EMISSION FROM ACTIVE GALAXIES

DUNCAN A. FORBES
Lick Observatory, University of California, Santa Cruz, CA 95064

AND

MARTIN J. WARD
Department of Physics, Nuclear Physics Laboratory, Keble Road, Oxford OX1 3RH, UK
*Received 1992 December 21; accepted 1993 April 21*

## ABSTRACT

We find a strong correlation between the 6 cm radio and near-infrared [Fe II] 1.64 $\mu$m line emission from the nuclei of active galaxies, including starburst, LINER, and Seyfert types. For starburst galaxies this correlation is simply explained in terms of fast shocks associated with supernova remnants. There is no obvious trend with nuclear activity type, suggesting that a similar mechanism, namely shocks, is responsible for the [Fe II] and radio emission in both starburst and Seyfert galaxies, although the origin of the shocks may be different. The nuclear radio emission from all the galaxies in our sample is largely nonthermal. The Br$\gamma$ and $H_2$ 1–0 $S(1)$ line luminosities also correlate with the 6 cm radio emission, but the dispersion is significantly greater than found for the [Fe II] emission, indicating a secondary relationship.

*Subject headings:* galaxies: active — galaxies: nuclei — galaxies: Seyfert — radiation mechanisms: miscellaneous — shock waves — supernovae: general

## 1. INTRODUCTION

The role of massive stars and supernovae in active galaxies—starburst, LINER, and Seyfert galaxies—is still controversial. One method for evaluating the importance of these stellar processes in a large sample of galaxies is to examine the relationships between multiwavelength data. For example, Ward (1988) found a good correlation between Brackett $\gamma$ strength and the low-energy X-ray emission from starburst nuclei. Both quantities are directly (via ionizing photons) or indirectly (via massive binaries) related to the presence of OB stars. Similarly there is the well-established and ubiquitous radio versus far-infrared correlation for galaxies of widely different optical activity class. In this case the link is thought to arise from the presence of supernova remnants (SNRs) that generate the radio synchrotron emission, and young massive stars whose optical/ultraviolet continuum is absorbed and then reradiated by dust mixed within the star-forming regions (starbursts), or throughout the galaxy, in the case of normal galaxies (Wunderlich, Klein, & Wielebinski 1987; Condon 1992, and references therein). Recently Sopp & Alexander (1991) found that the far-infrared and radio luminosities of radio-quiet quasars, and ultra-luminous infrared galaxies extend this correlation to very high luminosities. They suggest that a common sequence of massive star formation and associated SNRs in the host galaxies of these systems are responsible for the observed correlation.

In this paper we investigate the relation between the near-infrared emission line of [Fe II] at 1.64 $\mu$m and the 6 cm radio continuum emission from the nuclear region of active galaxies. The lines of [Fe II] are found to be strong cooling agents in Galactic and LMC SNRs (Graham, Wright, & Longmore 1990; Oliva, Moorwood, & Danziger 1989). Spectroscopic studies of nearby starburst galaxies also favor SNRs as the source of the [Fe II] emission (Moorwood & Oliva 1988; Greenhouse et al. 1991). Lester et al. (1990) have mapped the [Fe II] line emission in M82 and concluded that the [Fe II] emission follows the nonthermal radio emission and is therefore directly linked to SNRs. More recently, Fabry-Perot imaging of NGC 253 (Forbes et al. 1993b) and NGC 6240 (van der Werf et al. 1993) show direct spatial correspondence of the sites of [Fe II] 1.64 $\mu$m and 6 cm radio emission. If this spatial agreement occurs in general for all active galactic nuclei (AGNs), then we would expect a strong correlation between these two quantities when compared over similar aperture sizes. Examining the radio and infrared line properties over similar sized regions is an important advantage for our work compared to previous radio versus far-infrared studies, for which there are large differences between the radio beam and the *IRAS* aperture size. Here we report the excellent correlation found between the [Fe II] line and 6 cm radio emission, based on data assembled from the literature. We then discuss the implications of this for the origin of near-infrared [Fe II] and radio emission from the nuclei of active galaxies. We also investigate the relationships for Br$\gamma$ and $H_2$ 1–0 $S(1)$ line emission with 6 cm radio emission.

## 2. THE [Fe II] 1.64 MICRON AND 6 CENTIMETER RADIO DATA

We have searched the literature for published [Fe II] 1.64 $\mu$m fluxes of active galaxies. These data are from spectroscopic studies made using entrance apertures of typically about 6″ diameter, corresponding to a few hundred parsecs up to a kiloparsec, for the range of distances to the sample galaxies. The data are not corrected for extinction. Although this effect may be of significance in few cases, the extinction value is uncertain, and is very much less than for optical emission lines. In order to reduce the effects due to different aperture sizes, we have selected 6 cm radio observations made with a comparable beam size, or integrated over a similar region, to the aperture used for the [Fe II] observations. The list of active galaxies having both 6 cm radio measurements and [Fe II] detections or upper limits available using similar aperture sizes, is given in Table 1. We also list the Br$\gamma$ 2.17 $\mu$m and $H_2$ 1–0 $S(1)$ 2.12 $\mu$m

TABLE 1

THE SAMPLE

| Name | Activity | Distance (Mpc) | 6 cm (mJy) | Reference | [Fe II] 1.64 μm ($10^{-14}$ ergs $s^{-1}$ $cm^{-2}$) | Reference | Brγ 2.17 μm ($10^{-14}$ ergs $s^{-1}$ $cm^{-2}$) | Reference | $H_2$ 2.12 μm ($10^{-14}$ ergs $s^{-1}$ $cm^{-2}$) | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| NGC 1614 ....... | SB | 89.7 | 45 | 1 | 6.0 | 2 | 5.9 | 2 | 1.2 | 2 |
| IIZw40 ........... | SB | 16.1 | 22 | 3 | 4.3 | 2 | 6.7 | 2 | 2.0 | 2 |
| He2-10 ........... | SB | 12.0 | 55 | 4 | 9.7 | 5 | 4.4 | 5 | 1.4 | 2 |
| NGC 5253 ....... | SB | 6.0 | 75 | 6 | 9.7 | 5 | 15.0 | 5 | <1.0 | 2 |
| NGC 7714 ....... | SB | 57.4 | 15 | 7 | 4.2 | 2 | 3.0 | 2 | <1.0 | 2 |
| M82 ............. | SB | 6.0 | 44 | 8 | 16.0 | 9 | 20.0 | 9 | 2.9 | 9 |
| NGC 7552 ....... | SB | 29.9 | 28 | 10 | 10.0 | 2 | 8.3 | 2 | 2.9 | 2 |
| NGC 613 ......... | C | 29.9 | 42 | 11 | 4.0 | 2 | 1.4 | 2 | 1.8 | 2 |
| NGC 1365 ....... | C | 35.9 | 8.0 | 12 | 2.6 | 2 | 3.0 | 2 | 2.0 | 2 |
| NGC 7582 ....... | C | 29.9 | 69 | 13 | 4.2 | 2 | 3.5 | 2 | 2.0 | 2 |
| NGC 7469 ....... | C | 101.7 | 68 | 14 | 3.1 | 2 | 1.2 | 2 | 1.1 | 2 |
| NGC 3256 ....... | C | 56.2 | 42 | 15 | 6.8 | 2 | 4.1 | 2 | 2.8 | 2 |
| NGC 1808 ....... | L | 17.9 | 28 | 16 | 13.0 | 2 | 5.0 | 2 | 4.1 | 2 |
| NGC 253 ......... | L | 6.0 | 120 | 17 | 31.8 | 2 | 17.9 | 2 | 11.1 | 2 |
| NGC 6240 ....... | L | 149.5 | 80 | 18 | 16.1 | 2 | <0.6 | 2 | 21.0 | 2 |
| NGC 1097 ....... | L | 23.9 | 3.5 | 19 | <1 | 2 | <1 | 2 | <2 | 2 |
| NGC 5506 ....... | S2 | 41.9 | 160 | 13 | 6.3 | 2 | 5.7 | 2 | <1 | 2 |
| NGC 1068 ....... | S2 | 17.9 | 1090 | 18 | 47.3 | 5 | 13.6 | 5 | 15.0 | 20 |
| TOL 0109 ........ | S2 | 65.8 | 15 | 21 | <1 | 2 | <1 | 2 | <0.6 | 2 |
| NGC 7172 ....... | S2 | 47.8 | 1.8 | 22 | <0.6 | 2 | <0.5 | 2 | <0.7 | 2 |
| NGC 7590 ....... | S2 | 29.9 | 70 | 23 | <20 | 2 | <1 | 2 | <1 | 2 |
| NGC 4151 ....... | S1 | 17.9 | 120 | 24 | 16.0 | 25 | 3.0 | 26 | 18.2 | 25 |
| NGC 3227 ....... | S1 | 17.9 | 34 | 13 | 10.0 | 27 | ... | ... | 3.3 | 26 |
| NGC 2992 ....... | S1 | 41.9 | 77 | 13 | 5.8 | 27 | 0.6 | 28 | 1.4 | 28 |
| NGC 7314 ....... | S1 | 35.9 | 1.9 | 22 | <0.6 | 2 | <1 | 2 | <1 | 2 |
| NGC 4594 ....... | S1 | 12.0 | 118 | 19 | <5 | 2 | <1 | 2 | ... | ... |

REFERENCES:—(1) Hummel et al. 1987; (2) Moorwood & Oliva 1988; (3) Jaffe et al. 1978; (4) Allen et al. 1976; (5) Kawara et al. 1988; (6) Whiteoak 1970; (7) Condon 1980; (8) Kronberg et al. 1985; (9) Lester et al. 1990; (10) Forbes et al. 1993a; (11) Hummel et al. 1985; (12) Sandqvist et al. 1982; (13) Ulvestad & Wilson 1984; (14) Condon et al. 1991; (15) Forbes & Norris 1993; (16) Saikia et al. 1990; (17) Antonucci & Ulvestad 1988; (18) Condon et al. 1982; (19) Hummel et al. 1984; (20) Moorwood & Oliva 1990; (21) Ulvestad & Wilson 1989; (22) Unger et al. 1987; (23) Ward et al. 1980; (24) Johnson et al. 1982; (25) Rieke & Lebofsky 1981; (26) Fisher et al. 1987; (27) Ward et al. 1987 (assuming [Fe II] 1.64 μm = 0.71 [Fe II] 1.26 μm); (28) Kawara et al. 1990.

emission line fluxes for the same galaxies. In the case of NGC 253, NGC 1808 and M82, for which high-resolution 6 cm maps are available, we have summed the contribution from the compact radio sources over the appropriate region of the nucleus.

We selected the [Fe II] line at 1.64 $\mu$m rather than the line of the same species at 1.26 $\mu$m, because the latter, although stronger, is blended with a He I line. Also, fluxes for the line at 1.64 $\mu$m are more widely available in the literature.

## 3. ORIGIN OF THE RADIO AND [Fe II] EMISSION

The 6 cm radio continuum emission from the nuclei of Seyfert galaxies consists predominantly of nonthermal emission from optically thin synchrotron, with a small contribution from thermal free-free emission associated with star-forming regions (Edelson 1987). From previous studies of Seyfert galaxies it is known that the radio emission is often associated with jets or small-scale lobes, which are a powered by processes occurring on very small scales. In the case of starburst nuclei (without any evidence for Seyfert activity) the radio emission is dominated by nonthermal synchrotron processes arising from SNRs (Ho, Beck, & Turner 1990), and is often extended and diffuse. The contribution of thermal radio emission in the starbursts of Markarian galaxies may not be negligible (Stine 1992), but we have no such galaxies in our sample. There are also examples in which both compact (Seyfert) and diffuse (starburst) radio emission is found. Both radio jets and the radio emission from SNRs have essentially the same radio spectral index, so this parameter alone does not assist in distinguishing between radio emission associated with the presence of Seyfert or starburst type activity.

Near-infrared [Fe II] $^4D_{7/2}$–$^4F_{9/2}$ at 1.64 $\mu$m occurs in the extended transition region from partially to fully ionized gas. It is produced by electron collisions, such as occur behind fast ($v > 100$ km s$^{-1}$) moving shocks (e.g., Greenhouse et al. 1991) or by photoionization (e.g., Graham et al. 1990). The fast shocks associated with a SNR blast wave can effectively destroy dust grains, returning iron to the gas phase, thus enhancing the abundance. These two effects (ionization and enhanced abundance) make $Fe^+$ a strong cooling agent in the post-shock gas of a SNR, and this is the most likely source of [Fe II] emission in starburst galaxies (Greenhouse et al. 1991). The lack of neutral hydrogen in H II regions restricts the charge exchange with $H^0$ and therefore the abundance of $Fe^+$ (see Oliva, Moorwood, & Danziger 1989). These effects result in the large [Fe II]/Br$\gamma$ line ratios observed for SNRs compared to H II regions. For example [Fe II] 1.64 $\mu$m/Br$\gamma$ in the Orion star-forming region is $\sim$0.05, while that in Galactic SNRs is $\sim$50 (Moorwood & Oliva 1988). Photoionization may also provide a viable mechanism if it results in significant grain destruction, however, this is yet to be demonstrated. Possible mechanisms for the excitation of the near-infrared [Fe II] emission in Seyfert galaxies are discussed in the next section.

## 4. RESULTS AND DISCUSSION

In Figure 1*a* we show a plot of [Fe II] 1.64 $\mu$m line flux against the 6 cm radio flux density for similar aperture sizes. A clear correlation in flux is seen, which is also present when the luminosities are plotted (see Fig. 1*b*). We have fitted a regression line using the nonparametric Buckley-James survival analysis technique in order to correctly incorporate the upper limits given for [Fe II] in Table 1 (Isobe, Feigelson, & Nelson 1986). The dispersion about the regression line for flux is $\sigma = 0.28$ in the logarithm. Assuming that there is an intrinsic relationship between the nonthermal radio emission and the [Fe II] line strength, and observational errors do not dominate, there are two effects that could contribute to the scatter in Figure 1. Firstly, significant reddening would reduce the [Fe II] flux, whilst not affecting the associated radio flux. Secondly, there may be some contribution to the radio emission from thermal processes, although as mentioned above this is probably small. If there are cases in which the extinction and thermal radio contribution are both zero, then they should define an upper envelope for this relationship.

The correlation in Figure 1 implies a close relationship between the source of the synchrotron emission which produces the radio emission and the source of the [Fe II] emission. In starburst and LINER galaxies, where Forbes et al. (1992) find little evidence for nonthermal nuclear activity (other than SNRs), this relationship can be plausibly explained by the fast shocks associated with SNRs. The distribution of points in the correlation for Seyfert galaxies and composite systems (Seyfert plus starburst) are evenly spread amongst those corresponding

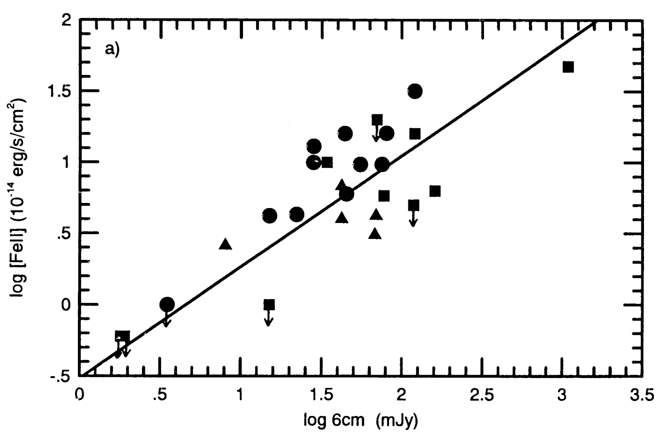


FIG. 1*a*

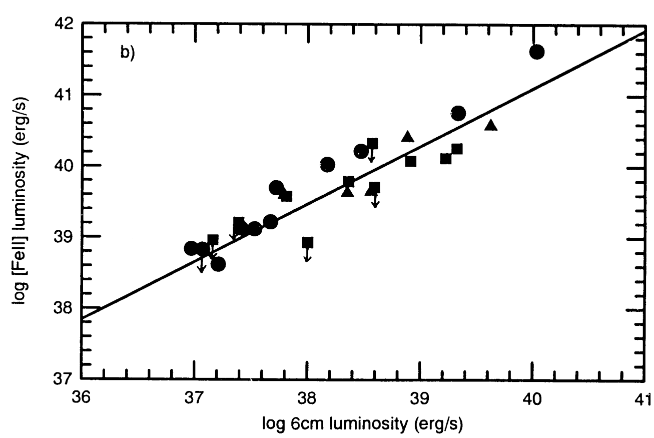


FIG. 1*b*

FIG. 1.—(*a*) [Fe II] 1.64 $\mu$m vs. 6 cm radio emission for galactic nuclei. Filled circles, triangles, and squares represent starburst or LINER galaxies, galaxies with a composite spectrum, and Seyfert galaxies, respectively. Also shown is the best-fit regression line from survival analysis, i.e., log [Fe II] = 0.78 ± 0.15 log 6 cm − 0.51, $\sigma = 0.28$. (*b*) Same as Fig. 1*a*, except data given in luminosity. The regression line is log [Fe II] = 0.82 ± 0.07 log 6 cm + 8.46, $\sigma = 0.27$.

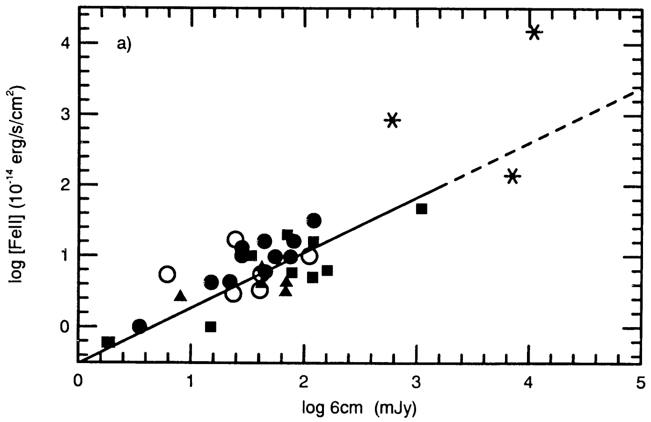


FIG. 2a

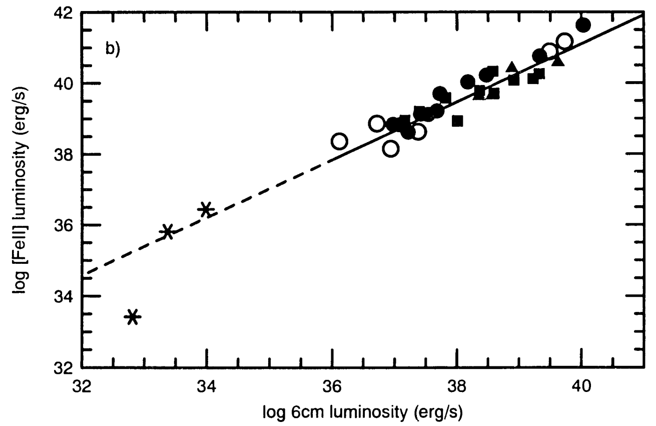


FIG. 2b

FIG. 2.—(a) [Fe II] 1.64 μm vs. 6 cm radio emission for galactic nuclei and Galactic/LMC SNRs. The SNRs are represented by stars, and six regions of enhanced [Fe II] emission in three galaxy nuclei by open circles. The dashed line is an extrapolation of the regression fit from Fig. 1. Upper limits are not shown in this Figure. (b) Same as Fig. 2a, except data given in luminosity.

to the LINER and starburst galaxies. We conclude that there is little or no trend in this plot with nuclear activity type. The simplest explanation for this would be that the same physical process is operating in all galactic nuclei, from those with LINER or starburst activity to Seyfert galaxies.

Figure 2 provides further support that the correlation is a consequence of processes associated with supernova activity. Here we replot Figure 1, with the same regression line, on an expanded scale and include two Galactic SNRs, one LMC SNR and small aperture ($\sim 2''$ diameter) data for three galaxies. We show the location of the RCW103, Kepler, and N49 SNRs. The distances and [Fe II] emission (corrected for extinction and isotropic emission) are from Oliva, Moorwood, & Danziger (1989). The radio measurements come from Weiler et al. (1986) for RCW103 and Kepler, and from Junkes (1991) for N49. The new galaxy data shown in Figure 2 are for the two nuclei of NGC 6240 (van der Werf et al. 1993), hotspot A and the nucleus of NGC 253 (Forbes et al. 1993b) and two bright [Fe II] regions in M82 (Greenhouse et al. 1991). All six sources are spatially associated with radio sources which indicate a contribution from nonthermal emission processes, i.e., SNRs.

The individual SNRs are consistent with the regression line, albeit with considerable dispersion. The sources within the nuclear region of NGC 6240, NGC 253, and M82 lie along the regression line and suggest either integrated supernova activity, or very luminous individual SNRs. However, the case for Seyfert galaxies requires separate consideration.

As discussed above, the 6 cm radio emission from the nuclei of active galaxies is mostly nonthermal, hence we do not predict a good correlation with parameters related to thermal free-free emission from star forming regions. Nevertheless the number of massive ionizing stars is also proportional to the supernova rate, so we would expect an indirect link between Brγ emission line strength and nonthermal radio emission. Figure 3 shows a definite correlation between Brγ and 6 cm radio emission. The dispersion about a best fit regression line in flux is $\sigma = 0.44$. This scatter is considerably more than that found for [Fe II], just as would be expected.

The excitation process of $H_2$ gas in galactic nuclei remains an open question with a variety of possible mechanisms under consideration (e.g., Sternberg & Dalgarno 1989; Moorwood & Oliva 1990). Greenhouse et al. (1991) find a relationship

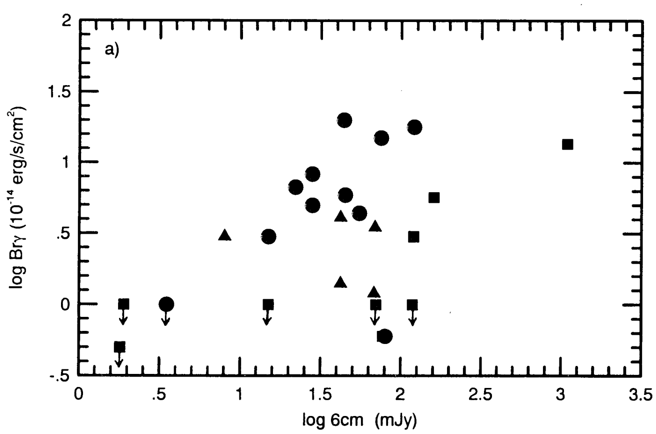


FIG. 3a

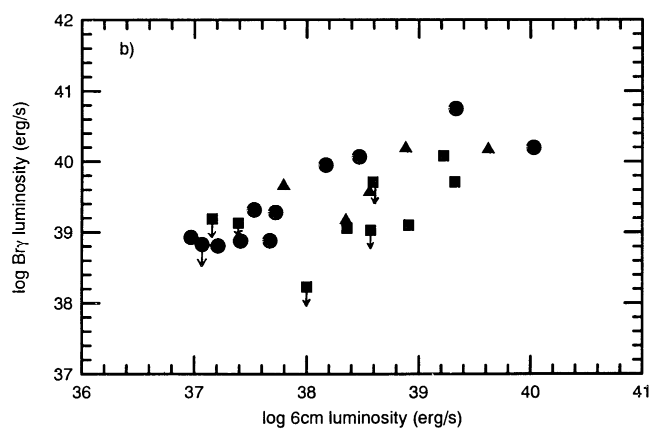


FIG. 3b

FIG. 3.—(a) Brγ 2.17 μm vs. 6 cm radio emission for galactic nuclei. A best-fit regression line from survival analysis is log Brγ = 0.56 ± 0.23 log 6 cm − 0.53, $\sigma = 0.44$. The same symbols are used as in Fig. 1. (b) Same as Fig. 3a, except data given in luminosity. The regression line is log Brγ = 0.53 ± 0.12 log 6 cm + 19.24, $\sigma = 0.40$.

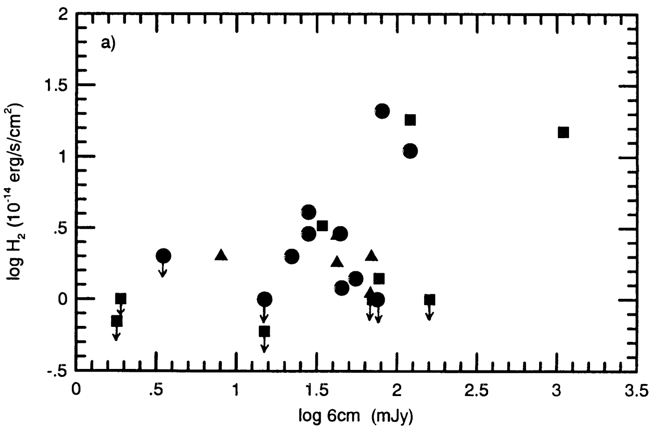


FIG. 4*a*

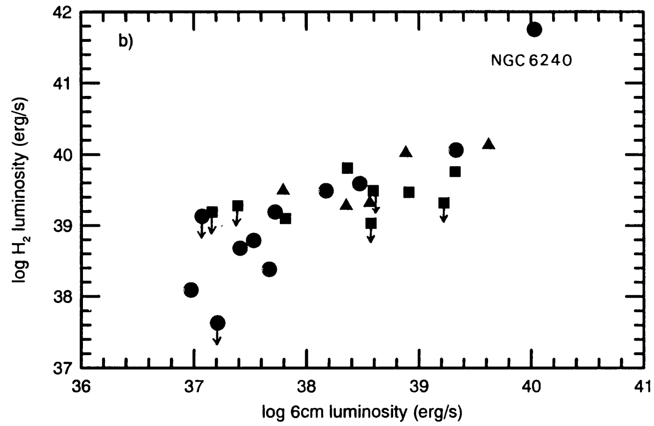


FIG. 4*b*

FIG. 4.—(*a*) $H_2$ 1–0 *S*(1) 2.12 $\mu$m vs. 6 cm radio emission for galactic nuclei. A best-fit regression line from survival analysis is log $H_2 = 0.64 \pm 0.21$ log 6 cm $- 0.77$, $\sigma = 0.37$. The same symbols are used as in Fig. 1. (*b*) Same as Fig. 4*a*, except data given in luminosity. The regression line is log $H_2 = 0.86 \pm 0.12$ log 6 cm $+ 6.27$, $\sigma = 0.40$.

between the luminosity of the [Fe II] 1.64 $\mu$m and $H_2$ 1–0 *S*(1) 2.12 $\mu$m detections (although they ignored the upper limits) for galactic nuclei, and suggest that the $H_2$ emission is related to supernova activity. We believe that these two quantities are only *indirectly* related since they are both measures of the integrated star formation in a galaxy. Evidence to support this view is given by the scatter ($\sigma = 0.37$) apparent in Figure 4*a*, in which we plot $H_2$ against 6 cm radio emission. This dispersion is higher than for [Fe II] and therefore suggests that, like Br$\gamma$, the correlation with 6 cm radio emission is secondary in nature. Further evidence that $H_2$ is not predominately excited by supernova events is given by the recent spatial mapping of the starburst galaxy NGC 253 (Forbes et al. 1993b). In the nuclear region of NGC 253 the $H_2$ more closely follows the Br$\gamma$ emission than that of [Fe II] 1.64 $\mu$m, indicating that $H_2$ is excited in the mass outflows and/or dense photodissociation regions of recent star formation.

If we now consider the case of the merging galaxy NGC 6240, Figure 4*b* shows that it is about 100 times more luminous in $H_2$ than any of the other galaxies. As suggested by several authors, this extraordinary luminosity appears to be generated by the large-scale slow shocks at the interface of the merging galaxies. The ratio of $H_2$ to 6 cm luminosity is also larger relative to the other galaxies, indicating that the radio emission has not been enhanced as a result of the collision. Similarly the slow shocks that have enhanced the $H_2$ emission have had little or no affect on the [Fe II] 1.64 $\mu$m emission (which require fast shocks) or Br$\gamma$. These conclusions are strongly supported by the Fabry-Perot imaging of van der Werf et al. (1993). The line images show that most of the $H_2$ emission in NGC 6240 is located between the two nuclei, i.e., at the shock working surface, whereas the [Fe II] 1.64 $\mu$m, the broad-band infrared emission and the 6 cm radio emission are largely confined to the two nuclei (see also Eales et al. 1990).

The correlations shown in Figures 1 and 2 suggest that the [Fe II] and radio emissions are intimately related. We have argued that the production processes are linked via SNRs, and the relation is apparently independent of nuclear activity type. However, as noted in § 3, it is generally believed that the nuclear radio emission in Seyfert galaxies can be largely attributed to processes associated with the AGN. If true, we might also expect the [Fe II] emission to have its origin in Seyfert activity. Indeed some Seyfert galaxies, but not all, have been observed to have broad ($\sim 700$ km s$^{-1}$) [Fe II] lines (see Moorwood & Oliva 1988; Mouri et al. 1990) suggesting an association with the narrow line region (NLR) clouds. Furthermore narrow-band imaging of the [Fe II] 1.64 $\mu$m line in NGC 1068 by Blietz et al. (1993), clearly shows an [Fe II] morphology associated with the radio jet structure, extending over many arcseconds, and without any obvious discrete sources. We now consider the alternative mechanisms for [Fe II] emission in Seyfert galaxies.

### 4.1. *Photoionization*

Photoionization from the compact Seyfert 1 continuum is regarded as a significant excitation source by Oliva & Moorwood (1990) for NGC 1068, and by Graham, Wright, & Longmore (1990) for NGC 4151. Similarly, Mouri et al. (1990) suggests that photoionization via X-ray heating is important in both of these galaxies. The [Fe II] emission in NGC 1068 has a similar position angle as the optical emission-line clouds providing qualitative support for photoionization, but shocks within the radio-emitting plasma are probably more important (Blietz et al. 1993).

As well as a viable excitation mechanism, an enhanced abundance of [Fe II] is needed in order to produce the relatively high [Fe II]/Br$\gamma$ line ratios commonly observed in galactic nuclei (and SNRs). Greenhouse et al. (1991) argue that this requires iron-enriched supernova ejecta or grain destruction via fast shocks. The importance of enhanced iron abundance is disputed by Mouri, Kawara, & Taniguchi (1993) who present evidence based on optical [Fe II] line ratios that suggest ionization effects are dominant. We speculate that photoionization from a high-energy source such as X-ray heating may also destroy grains. However, as noted by Oliva & Moorwood (1990), the X-ray heating models of Krolik & Lepp (1989) describe heating within the obscuring torus on scales of a few parsecs, whereas the [Fe II] emission is extended to hundreds of parsecs in NGC 1068.

There is a well established correlation between optical forbidden line strength (notably [O III] 5007 Å) and radio power in Seyfert galaxies (see Whittle 1992), so a correlation between radio and [Fe II] emission would also be expected. The main difficulty with photoionization may not be associated with the process itself, but rather to understand why the ionizing continuum should produce [Fe II] with a similar ratio to the radio emission as is found in the other nuclear activity classes, such as starburst galaxies.

### 4.2. *Radio Jet–Induced Shocks*

Shocks produced by a radio jet have been proposed by Norman & Miley (1984) to explain the excitation of the optical permitted Fe II emission in AGNs, but the densities in these regions are higher than in the regions emitting the forbidden [Fe II] lines. Moorwood & Oliva (1988) and Kawara, Nishida, & Taniguchi (1988) suggest that these shocks may also contribute to the excitation of near-infrared [Fe II]. With a plasma velocity in the NLR of a few hundred km $s^{-1}$, radio jets would efficiently destroy dust grains, thus enhancing the gas-phase abundance of iron.

This mechanism is favored by Blietz et al. (1993) as the origin of the [Fe II] emission in NGC 1068. Recent observations of NGC 1068 show that shock excitation can account for some of the ultraviolet emission lines in the spectrum of the nucleus (Kriss et al. 1992). The radio structures of Seyfert galaxies in our sample range from slightly resolved morphologies with no obvious radio jets (such as NGC 3227), to those with linear structures like NGC 4151 and the classic bow shock seen in NGC 1068. The question remains whether these shocks can produce [Fe II] and radio emission with a similar efficiency to that produced by the shocks associated with SNRs in starburst galaxies.

A potentially useful diagnostic, between shocks and photoionization, is the line ratios of [Fe II]. Unfortunately, there have been no systematic studies of both the optical and near-infrared [Fe II] line ratios, which are density and temperature sensitive. Using the optical [Fe II] lines alone, Mouri et al. (1993) favored photoionization but could not rule out shock excitation. As an alternative approach, we performed a crude analysis of the [Fe II] 0.8617 $\mu$m/[Fe II] 1.64 $\mu$m line ratio using published data for five Seyferts, which gives a range of $\sim$0.2–1.5 with large uncertainties. For typical NLR densities, the temperature inferred for the lower values are consistent with shock excitation. (We note that the two galaxies with the highest ratio, and therefore temperature, have pronounced linear radio structures.)

In view of the difficulties facing the photoionization model, and the support for the jet-induced shock model provided by the imaging of Blietz et al. (1993) we favor the latter mechanism for [Fe II] emission in Seyfert galaxies. However, we do not rule out the possibility that a significant fraction of the [Fe II] and radio emission from the nuclear region of some Seyferts is due to SNRs (see also Colina & Perez-Olea 1992).

## 5. CONCLUSIONS

We find a strong correlation between the [Fe II] 1.64 $\mu$m line and 6 cm radio (flux and luminosity) for a sample of active galaxies. This correlation does not appear to depend on the type of activity that dominates the nuclear emission. In starburst galaxies, and Seyferts with composite activity, the relation can be explained by the presence of SNRs. The [Fe II] line widths in Seyfert nuclei, and the emission line morphology in the only case so far studied (NGC 1068), suggest a different origin. The fact that Seyferts fit the correlation so well, in common with the other galaxy types, suggests a fundamental link via the physical process involved. We therefore favor a model for Seyfert galaxies, in which shocks formed by the radio jet/gas interaction produce most of the near-infrared [Fe II] emission. Further narrow-band imaging in the [Fe II] emission line of both starburst and Seyfert galaxies, and comparison to their radio structures, should provide the definitive test of the proposed models.

We thank the following persons for useful discussions, Roberto Cid Fernandes, Tim Heckman, Paul van der Werf, and Mark Whittle. We also thank the referee for many suggestions that improved the final manuscript.

## REFERENCES

Allen, D. A., Wright, A. E., & Goss, W. M. 1976, MNRAS, 177, 91
Antonucci, R. R. J., & Ulvestad, J. S. 1988, 330, L97
Blietz, M., et al. 1993, ApJ, in press
Colina, L., & Perez-Olea, D. 1992, MNRAS, 259, 709
Condon, J. J. 1980, ApJ, 242, 894
———. 1992, ARA&A, 30, 575
Condon, J. J., Condon, M. A., Gisler, G., & Puschell, J. J. 1982, ApJ, 252, 102
Condon, J. J., Frayer, D. T., & Broderick, J. J. 1991, AJ, 101, 362
Eales, S. A., Becklin, E. E., Hodapp, K. W., Simons, D. A., & Wynn-Williams, C. G. 1990, ApJ, 365, 478
Edelson, R. A. 1987, ApJ, 313, 651
Fisher, J., Geballe, T., Smith, H. A., Simon, M., & Storey, J. W. V. 1987, ApJ, 320, 667
Forbes, D. A., & Norris, R. P. 1993, in preparation
Forbes, D. A., Norris, R. P., Williger, G. M., & Smith, R. C. 1993a, in preparation
Forbes, D. A., Ward, M. J., DePoy, D. L., Boisson, C., & Smith, M. G. 1992, MNRAS, 254, 509
Forbes, D. A., Ward, M. J., Rotaciuc, V., Blietz, M., Genzel, R., Drapatz, S., van der Werf, P., & Krabbe, A. 1993b, ApJ, 406, L11
Graham, J. R., Wright, G. S., & Longmore, A. J. 1990, ApJ, 352, 172
Greenhouse, M. A., Woodward, C. E., Thronson, H. A., Rudy, R. J., Rossano, G. S., Erwin, P., & Puetter, R. C. 1991, ApJ, 383, 164
Ho, P. T. P., Beck, S. C., & Turner, J. L. 1990, ApJ, 349, 57
Hummel, E., Pedlar, A., van der Hulst, J. M., & Davies, R. D. 1985, A&AS, 60, 293
Hummel, E., van der Hulst, J. M., & Dickey, J. M. 1984, A&A, 134, 207
Hummel, E., van der Hulst, J. M., Keel, W. C., & Kennicutt, R. C. 1987, A&AS, 70, 517
Isobe, T., Feigelson, E. D., & Nelson, P. I. 1986, ApJ, 306, 490
Jaffe, W. J., Perola, G. C., & Tarenghi, M. 1978, ApJ, 224, 808
Johnson, K. J., Elvis, M., Kjer, D., & Shen, B. S. P. 1982, ApJ, 262, 61
Junkes, N. 1991, in The Magellanic Clouds, ed. R. Haynes & D. Milne (Dordrecht: Kluwer), 347
Kawara, K., Nishida, M., & Gregory, B. 1990, ApJ, 352, 433
Kawara, K., Nishida, M., & Taniguchi, Y. 1988, ApJ, 328, L41
Kriss, G., et al. 1992, ApJ, 394, L37
Krolik, J. H., & Lepp, S. 1989, ApJ, 347, 179
Kronberg, P. P., Biermann, P., & Schwab, F. R. 1985, ApJ, 291, 693
Lester, D. F., Carr, J., Joy, M., & Gaffney, N. 1990, ApJ, 352, 544
Moorwood, A. F. M., & Oliva, E. 1988, A&A, 203, 278
———. 1990, A&A, 239, 78
Mouri, H., Nishida, M., Taniguchi, Y., & Kawara, K. 1990, ApJ, 360, 55
Mouri, H., Kawara, K., & Taniguchi, T. 1993, ApJ, 406, 52
Norman, C., & Miley, G. 1984, A&A, 141, 85
Oliva, E., & Moorwood, A. F. M. 1990, ApJ, 348, L5
Oliva, E., Moorwood, A. F. M., & Danziger, I. J. 1989, A&A, 214, 307
Rieke, G. H., & Lebofsky, M. J. 1981, ApJ, 250, 87
Saikia, D. J., Unger, S. W., Pedlar, A., Tates, G. J., Axon, D. J., Wolstencroft, R. D., Taylor, K., & Gyldenkerne, K. 1990, MNRAS, 245, 397
Sandqvist, A., Joraster, S., & Lindblad, P. O. 1982, A&A, 110, 336
Sopp, H. M., & Alexander, P. MNRAS, 251, 14P
Sternberg, A., & Dalgarno, A. 1989, ApJ, 338, 197
Stine, P. C. 1992, ApJS, 81, 49
Ulvestad, J. S., & Wilson, A. S. 1984, ApJ, 285, 439
———. 1989, ApJ, 343, 659
Unger, S. W., Lawrence, A., Wilson, A. S., Elvis, M., & Wright, A. E. 1987, MNRAS, 228, 521
van der Werf, P., Genzel, R., Krabbe, A., Blietz, M., Drapatz, S., Ward, M. J., & Forbes, D. A. 1993, ApJ, 405, 522

Ward, M. J. 1988, MNRAS, 231, 1P
Ward, M. J., Geballe, T., Smith, M., Wade, R., & Williams, P. 1987, ApJ, 316, 138
Ward, M. J., Penston, M. V., Blades, J. C., & Turtle, A. J. 1980, MNRAS, 193, 564
Weiler, K. W., Sramek, R. A., Panagia, N., van der Hulst, J. M., & Salvati, M. 1986, ApJ, 301, 790
Whiteoak, J. B. 1970, Astrophys. Lett. (London), 5, 29
Whittle, M. 1992, ApJS, 79, 49
Wunderlich, E., Klein, U., & Wielebinski, R. 1987, A&AS, 69, 487