INFRARED [FeII] AND H_2 LINE EMISSION IN ACTIVE GALACTIC NUCLEI*

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ABSTRACT. Infrared spectra around [FeII](1.644μm), H_2 (v = 1-0 S(1) at 2.121μm) and Brγ (H 7-4 at 2.167μm) have been obtained of 35 emission line nuclei whose optical spectra range from pure HII region-like to Seyfert 1. All three emission lines have been detected in a large fraction of those nuclei exhibiting starburst activity but not in "pure" Seyferts. The highest detection frequency, however, was found for composite nuclei showing evidence for both starburst and Seyfert activity. Several arguments suggest that both the [FeII] and H_2 are shock excited and could be largely attributed to supernova remnants. The fact that the [FeII]/Brγ and H_2/Brγ ratios tend to be somewhat larger in composite than in pure starburst nuclei, however, plus significant spatial displacements between the [FeII] and H_2 emitting regions found recently during follow-up observations of selected galaxies suggest that large scale phenomena, e.g. SN winds or mass outflows from AGN, may also be important.

1. INTRODUCTION

Perhaps the most interesting result of exploratory infrared spectroscopy of galactic nuclei has been the discovery of [FeII] and H_2 emission lines with intensities comparable to and sometimes exceeding that of the Brγ hydrogen recombination line. These lines appear to be valuable tracers of gas which is shock heated by supernova remnants, galaxy mergers and possibly mass outflows from active nuclei.

Following the initial detection of the H_2 vibrational-rotational lines around 2μm in NGC 1068 (Thompson et al., 1978) and a weak feature attributed to [FeII](1.644μm) in M82 (Rieke et al., 1980), progress was relatively slow for several years with further detections limited to a few prominent active nuclei and interacting/starburst systems (Rieke and Lebofsky, 1981; Fischer et al., 1983; Heckman et

*) Based on observations made at the European Southern Observatory.

D. E. Osterbrock and J. S. Miller (eds.), Active Galactic Nuclei, 365–371.

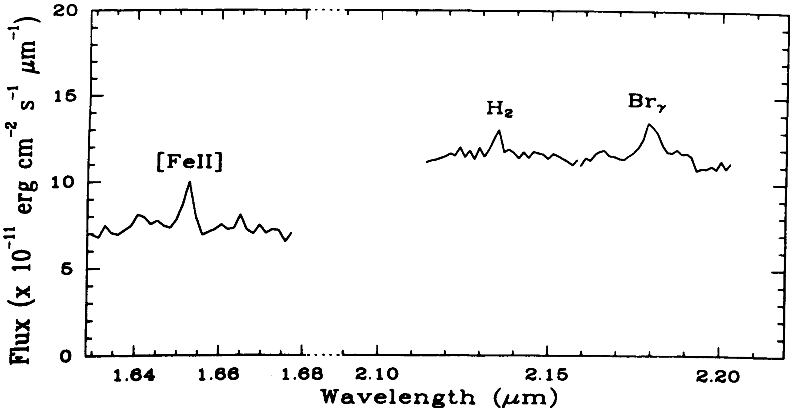

Fig. 1: IRSPEC spectrum of NGC 5506 (S2).

al., 1986; Joseph et al., 1987). With the availability of the IRSPEC grating/array spectrometer at the ESO 3.6 m telescope at the end of 1985, therefore, we began a more systematic search for [FeII](1.644μm), H_2 (v = 1-0 S(1), 2.121μm) and Brγ (H 7-4, 2.166μm) line emission in a sample of 35 galactic nuclei selected to represent the full range of optical emission line activity from pure HII region-like to Seyfert 1.

As the survey data will be published in detail elsewhere (Moorwood and Oliva, 1988), we restrict ourselves here to a summary of the main results, present some more recent observations of selected galaxies and discuss briefly the possible origin of these lines.

2. THE [FeII](1.644μm), H_2(2.121μm), Brγ(2.166μm) SURVEY

Spectra of 12 HII, 3 LINER, 9 Seyfert 2, 4 Seyfert 1 and 7 composite Seyfert/HII nuclei as classified according to the precepts of Véron-Cetty and Véron (1986) were obtained using a 6×6 arcsec aperture and R = 10^3 at 1.64μm and R = 1.5 10^3 around 2μm.

As the main topic here is active nuclei we show in Fig. 1 a spectrum of the S2/NLX galaxy NGC 5506 as a rare example of [FeII] and H_2 emission from an active nucleus which does not exhibit obvious evidence of starburst activity and one of the few cases where the lines can just be resolved at our resolution.

Fig. 2 shows histograms of detection frequency versus optical spectrum type for each of the three infrared emission lines. Except for Seyfert 1's, all three lines are detected in nuclei of all spectral types but with a clear peak on the composites. Two of the three detected Seyfert 2's, NGC 4965 and Circinus also exhibit some infrared properties more characteristic of starburst nuclei (Moorwood and Glass, 1984) and the third is NGC 5506 (see Fig. 1) for which evidence of star formation activity is weaker but which does show 9.7μm absorption and a possible 3.28μm emission feature (Moorwood and Salinari, 1981) not normally observed in Seyfert nuclei. Fig. 3 is a line ratio diagram of [FeII]/Brγ versus H_2/Brγ which reveals some

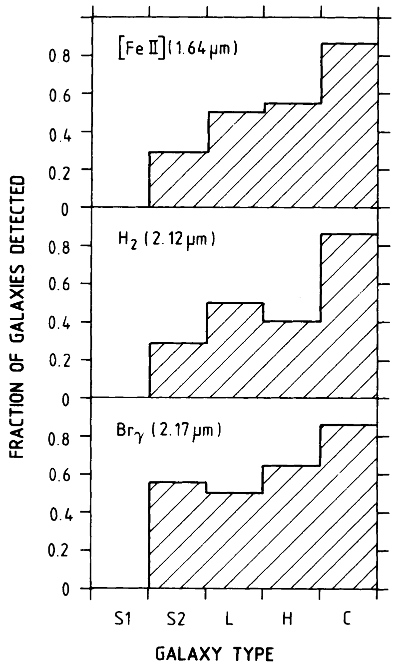

Fig. 2: Detection frequency versus spectral type for the 30 galaxies at $z < 0.01$.

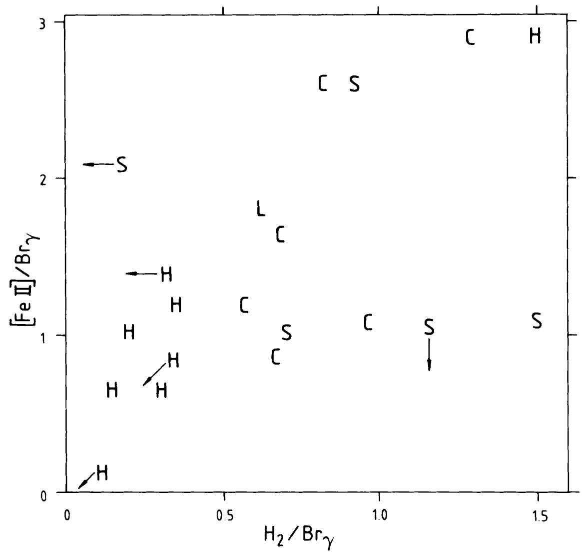

Fig. 3: Line ratio diagram showing some segregation between HII galaxies and those containing AGN.

segregation between the "pure" HII/starburst nuclei and those containing an active nucleus which tend to exhibit larger ratios, particularly $H_2/Br\gamma$. It should also be noted that [FeII] is brighter than $Br\gamma$ in more than half the sample.

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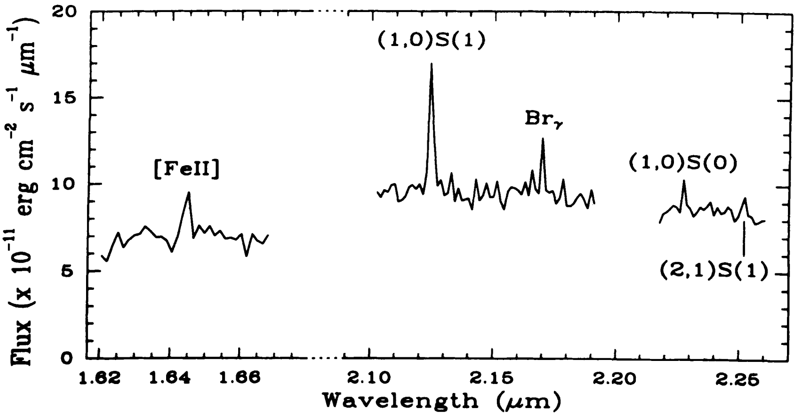

Fig. 4: IRSPEC spectrum of NGC 4945 (S2/composite).

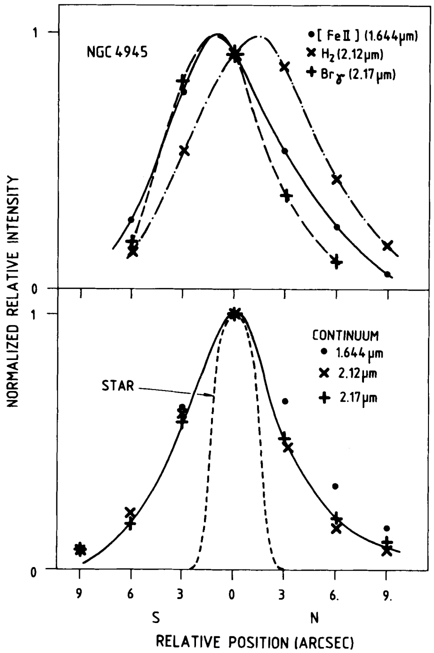

Fig. 5: Spatial distribution of the [FeII], H_2 and Brγ line emission in NGC 4945 (upper panel) and of the continuum emission under these lines (lower panel).

3. SPATIAL DISTRIBUTION OF THE IR LINE EMISSION

As part of a follow-up programme of more detailed observations we have recently made linear scans of several nuclei with IRSPEC, using a narrower 3 arcsec slit. The most complete data and perhaps most significant result were obtained in the case of NGC 4965. Fig. 4 shows a

https://doi.org/10.1017/S007418090014135X Published online by Cambridge University Press

spectrum of this galaxy which exhibits extremely pronounced H_2 (1-0 S(1)) line emission but only a very weak 2-1 (S1) line, implying that any contribution from UV fluorescently excited H_2 is negligible. Fig. 5 shows the spatial distributions of the [FeII], H_2 and Brγ line intensities with, below, the corresponding continuum distributions and the response obtained from scanning a star in the same way. The line and continuum profiles are clearly resolved with FWHM ≃ 6 arcsec (≃ 250 pc at 8 Mpc) but the most striking results are the ≃ 3 arcsec displacement of the H_2 emission from the [FeII] and Brγ and the fact that the lines appear to peak on either side of the nucleus as defined by the continuum profiles. A similar shift between [FeII] and H_2 also appears to be present in NGC 3256 and the Brγ emission in this case is more extended. In NGC 6240, although more distant (z = 0.025), the [FeII] and H_2 lines are brighter and spatially extended compared with our slit but exhibit no measurable displacement.

4. ORIGIN OF THE [FeII] AND H_2 EMISSION

Infrared [FeII] lines are not expected to be bright in HII regions because of the extremely low fractional abundance of Fe^+ ([FeII]/Brγ = 0.06 in the Orion nebula). The lack of detectable infrared lines in "pure" Seyfert nuclei is also not surprising given the apparent absence of [FeII] (5199 Å and 7155 Å) which should be brighter under these conditions. Shock heated gas therefore is considered to be the most likely source of the [FeII](1.644μm). Models for interstellar shocks at v > 50 km s^{-1} (see e.g. Shull and Draine, 1987) show that Fe^+ is the dominant ionization stage; enhancement of iron due to grain destruction and temperatures of a few × 10^3K which are sufficient to populate the upper level of this transition. The resulting predictions of [FeII]/Brγ ≃ 50 are also in good agreement with recent observations of supernova remnants (Graham et al., 1987; Oliva et al., 1988). These SNR observations also yield [FeII](1.644μm) luminosities of up to ~ 800 $L_\odot$. In the starburst nuclei therefore it seems most plausible to attribute the [FeII] emission to SNR and the Brγ to HII regions. Although detailed modelling is not yet possible, Moorwood and Oliva (1988) have shown that the [FeII]/Brγ ratios are consistent with the ratios of SN to ionization rates predicted by existing starburst models due to Rieke et al. (1980) and Gehrz et al. (1983) if the more luminous galactic and LMC SNR's are typical for starburst nuclei.

H_2 emission is also ubiquitous in galactic star forming regions where it is generally attributed to shock heating by low velocity shocks (< 50 km s^{-1}) driven by mass outflows from forming massive stars. Recent mapping of SNR's (Burton et al., 1988; Oliva et al., 1988) however has revealed the presence of shock excited H_2 with H_2(2.121μm) line luminosities in excess of the most luminous galactic star forming regions. As the H_2/[FeII] line ratios in these cases are also similar to those observed in galactic nuclei it is possible therefore that SNR could account for both the [FeII] and H_2 emission. Fluorescent excitation of H_2 by UV photons is also possible but the weakness of the 2-1 (S1) line relative to 1-0 (S1) observed now on several galactic nuclei (see Fig. 4 and Joseph et al., 1987) suggests that its contribution is negligible. (Recent observations by Puxley et al. (1988) however indicate that fluorescent excitation may dominate at larger distances from the nucleus in some cases.)

As evidence for circumnuclear star formation is a commom feature of the detected AGN's it is possible also in this case that at least some and possibly all of the [FeII] and H_2 emission is associated with SNRs. Although the [FeII] and H_2 to Brγ ratios are observed to be somewhat larger than in the pure starburst nuclei there is no sharp division (see Fig. 3) indicative of a completely different emission mechanism and this effect could for example simply reflect a higher gas density in the vicinity of AGN's. The discovery of spatial displacements between the [FeII] and H_2 emission reported above however appears to provide observational evidence that shock excitation mechanisms operating over much larger scales than individual SNR's are present in some cases. In the galactic SNR RCW 103 the H_2 emission is displaced by about 0.5 pc relative to [FeII] in the direction away from the remnant centre (Oliva et al., 1988) where the blast wave has presumably both hit molecular material and slowed down. If the source of shock excitation in galactic nuclei is a wind resulting from the collective effect of SNR's then this effect might be scaled up. Alternatively, both the observed [FeII] and H_2 "excesses" and their spatial displacement may be regarded as evidence for additional shock excitation of circumnuclear gas by mass outflow from the active nucleus as postulated previously for H_2 emission for NGC 7469 by Heckman et al. (1986).

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DISCUSSION

DE ROBERTIS Can you tell us your quantitative definition of "composite nucleus"?

MOORWOOD We have adopted the classification of Véron-Cetty and Véron (*Astron. Ap. Suppl.*, **66**, 335, 1986) based on line profile-fits to Hα and [N II]. Identifying double line systems clearly depends on their relative velocities, widths, and intensities so there is no strict quantitative definition. Details of the fits kindly supplied by M.-P. Véron-Cetty generally show comparable Hα from the two components with apertures of a few arcsec. Spatially resolved spectra have also confined the presence of H II regions within a few arcsec of active nuclei in several cases.

PALOUS Stars form in clumps (associations, star clusters). Subsequent evolution of massive stars in groups produce supernovae and expanding multi-supernovae remnants. Are these multi-supernova remnants also expected in AGNs?

MOORWOOD Very little is known about the structure of circumnuclear star forming regions in AGNs. Both in them and in starburst nuclei however, the density of star formation must generally be much higher than in the disk of our galaxy where the phenomena you mention are seen. It is therefore possible that the supernova remnants produced by exploding massive stars merge together and form larger scale systems, bubbles, SNR winds, etc.

SMITH Wright and Graham have used the UKIRT to discover and image *filaments* of H_2 extending over several minutes of arc in the Cygnus loop supernova remnant.