Emission Lines in Active Galaxies: New Methods and Techniques
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Near-Infrared Emission Lines in AGNs

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Abstract. Near-infrared high-resolution imaging and spectroscopic observations of NGC 7469, Mrk 231, *IRAS* F10214+4724, and Circinus are presented. They indicate the presence of extended star-forming activity in the vicinity of the active nuclei of these galaxies on scales between 10 pc and 1 kpc from the nuclei. The very different distance scales covered by these objects show that the coexistence of AGN and star-formation activity is a common phenomenon. A first-order evolving star-cluster model calculation shows that we are beginning to understand the history and evolution of these circumnuclear star-forming regions.

1. Introduction

Recent evidence shows that star formation in the vicinity of AGNs is a fairly common phenomenon. The 1 kpc diameter starburst ring in the Seyfert 2 galaxy NGC 1068 and its dynamical connection to the central region by a stellar bar is just one well-studied example (Helfer & Blitz 1995; Tacconi et al. 1994; Thronson et al. 1989). However, not very much is yet known about the morphology, history, evolution, and the physical characteristics of these circumnuclear star-forming regions. Presently unanswered questions are (1) how close to the AGN itself the star-forming regions can be traced and (2) how the scenario changes as one goes to high-z galaxies. In trying to draw a more general picture, our group is undertaking a program to identify, resolve, and characterize circumnuclear starburst regions around AGNs at very different distances ranging from a few Mpc out to $z > 2$. The near-infrared wavelength range is best suited for such a study not only because the extinction is ten times lower compared to the visible, but also because of the plethora of diagnostic emission and absorption lines available in these bands. The data being presented here have been obtained with several of our instruments: the high-resolution camera *SHARP* (Hofmann et al. 1993), the integral-field spectrometer *3D* (Krabbe et al. 1995, Weitzel et al. 1996 and the first-order seeing corrector *ROGUE* (Thatte et al. 1995).

2. NGC 7469

The well-studied example NGC 7469 is a classical Seyfert 1 at a distance of 66 Mpc ($1'' = 320$ pc), and has a total mid- and far-infrared luminosity of $3 \times 10^{11}\, L_\odot$. The AGN is surrounded by a $\sim 4''$ diameter starburst ring seen nearly

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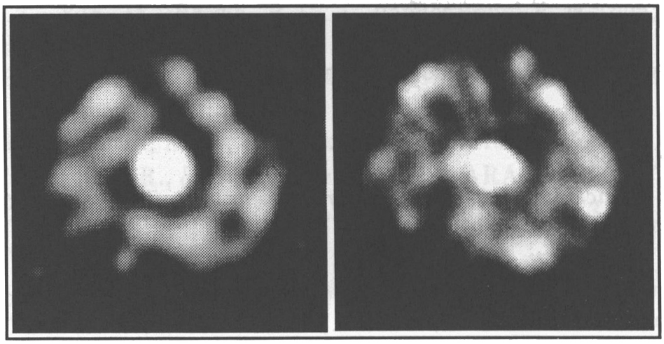

Figure 1. NGC 7469 high-resolution broad-band images. *Left: J*-band 1.25 μm with *SHARP* (Genzel et al. 1995). *Right: I*-band 0.9 μm *HST* WFPC. The field size is $5'' \times 5''$ with north to top and east to left.

face-on on the high-resolution NIR continuum image in Fig. 1 (Genzel et al.1995) as well as on the archival *HST* WFPC image.

The morphologies of the visible and NIR images are in excellent agreement. The main contributors to the NIR luminosity of the ring are the late-type stars which are delineated in the CO overtone absorption band depths at 2.3 μm. The spatial correlation between $V - K$ data and mid-infrared and radio data indicate that dust clouds embedded in the stellar distribution locally affect the visible an NIR emission distribution (Genzel et al. 1995). They can account for the morphological differences between the two images. NGC 7469 is gas rich and about $1.5 \times 10^{10}\,M_\odot$ of molecular gas is concentrated within 0.8 kpc of the nucleus (Tacconi et al. 1996). The presence of a starburst in the ring is indicated by several arguments (Genzel et al. 1995):

- The dynamical mass within the ring ($4.5 \times 10^9\,M_\odot$) cannot be matched with the assumption that all K-band flux originates from late-type stars only. Instead the mass/light ratio requires the presence of supergiants which are young and must have formed recently.
- The high 100 μm *IRAS* flux (35 Jy) and the large S100/S12 ratio (25, as compared to ~ 5 for other *IRAS* Seyfert 1 galaxies; Roche et al. 1991).
- A $5''$ extended region of [O III] and atomic-hydrogen emission lines, as well as 3.3 μm and 8–13 μm unidentified spectral features ascribed to PAHs (Mazzarella et al. 1994; Miles, Houck, & Hayward 1994).
- A similar-sized region of nonthermal radio continuum emission of knotty morphology (Wilson et al. 1991).
- The ring itself as a morphological feature.

We were able to derive physical parameters for the ring by applying an evolving star-cluster model, which shows that all the observations can be ex-

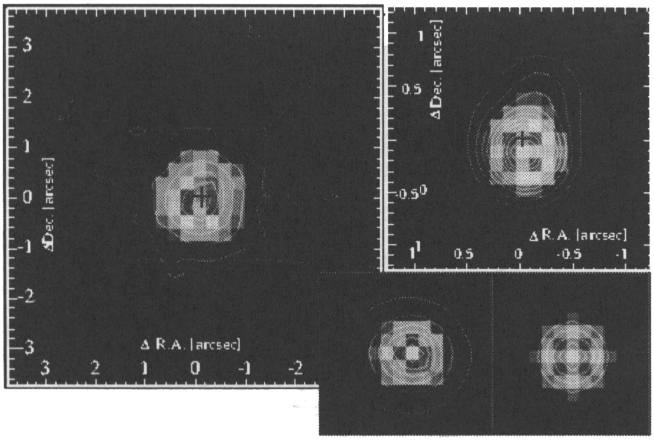

Figure 2. Molecular hydrogen in Mrk 231 (Krabbe et al. 1997). *Left:* Sum of H_2 S(1), S(2), S(3) 1–0 emission lines. *Bottom left:* Weighted average of the off-line continuum. *Upper right:* CLEANed image re-convolved to 0″.8 resolution. *Bottom right:* Corresponding beam.

plained by a powerful starburst (Genzel et al. 1995). The model is explained fully by Krabbe, Sternberg, & Genzel 1995 and uses solar-metallicity stellar-evolutionary tracks by Maeder & Meynet (1988) and Schaerer et al. (1993). Although there is not a unique solution, the results consistently show that the starburst age is between 10^7 and 10^8 years and the total stellar mass formed is $\sim 5 \times 10^8 M_\odot$. The star-formation rate is $\sim$ 20–60 $M_\odot\,\mathrm{yr}^{-1}$ for constant star formation and $\sim$ 200 $M_\odot\,\mathrm{yr}^{-1}$ for a decaying starburst. The most important result here is that the starburst contributes more than half of the total IR luminosity of the nuclear region including the Seyfert 1 nucleus.

3. Mrk 231

The ultraluminous Seyfert 1 galaxy Mrk 231 ($L_{ir} \approx 3.5 \times 10^{12} L_\odot$) is about 2.5 times farther away than NGC 7469 and the spatial scale of 0.8 kpc arcsec^{-1} makes it more difficult to resolve spatially the circumnuclear morphology. Yet there are several indicators for circumnuclear starburst activity. They suggest that Mrk 231 might exhibit a starburst quite comparable to that in NGC 7469 (Krabbe et al. 1997):

- The combined H_2 S(1), S(2), S(3) 1–0 emission lines obtained with *3D* show, for the first time in an ultraluminous galaxy, the presence of an extended circumnuclear hot molecular gas (Fig. 2). The diameter of this region is $\sim$ 1 kpc, similar to those found in NGC 7469 and NGC 1068.
- The K-band spectrum of the nuclear region indicates the presence of a central stellar concentration (Fig. 3), as we have seen previously in NGC

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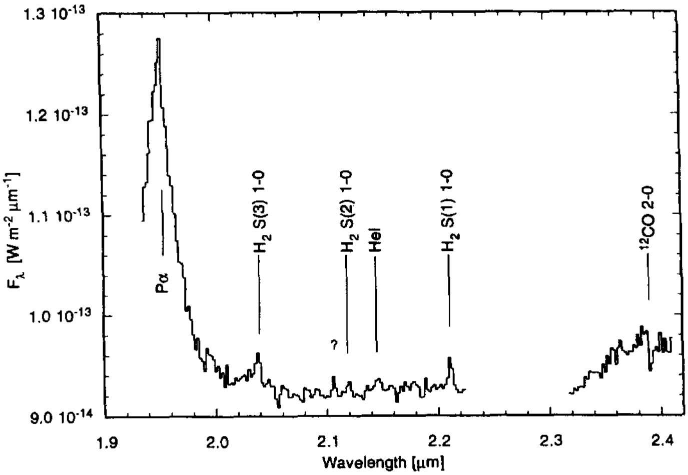

Figure 3. *3D* K-band spectrum of Mrk 231 within a $2''.5 \times 2''.5$ box, centered on the nucleus (Krabbe et al. 1997). The overall slope of the spectrum has been removed.

7469 (Genzel et al. 1995) and NGC 1068 (Thatte et al. 1997). The absorption feature is, however, diluted by hot dust emission or a nonthermal AGN continuum so that further constraints on the stellar type are difficult. The He I/Brγ ratio, however, implies an effective stellar temperature in the cluster of $\sim$ 37000 K, suggesting ongoing star formation with an upper mass cut-off $\geq 60\,M_\odot$.

- Since Mrk 231 shows a quasi-FIR blackbody spectrum (Downes, Solomon, & Radford 1993), the minimum radius of the FIR-emitting zone is determined from the $60\,\mu$m/$100\,\mu$m color temperature of 40 K to be at least 260 pc. Such a large radius indicates that a considerable fraction of the total infrared luminosity must emerge from circumnuclear star-forming regions at radii very much comparable to the H_2-emitting regions. The circumnuclear region is molecular rich. It contains a cold molecular mass of $2.4\times10^{10}\,M_\odot$ (Bryant & Scoville 1996).
- The UV spectrum displays characteristics similar to those of starburst galaxies, showing weak, narrow Lyα and Mg II λ2798 emission lines with no trace of the 2200 Å extinction feature (Lipari, Colina, & Machetto 1994). Ultraviolet spectropolarimetry of the central region shows a decrease in the degree of polarization, interpreted as due to dilution by an unpolarized blue stellar light. This stellar component begins to dominate the UV continuum at 2200 Å and explains why the continuum is still rising at 1600 Å (Smith et al. 1995).

If star formation is in fact associated with the hot molecular gas and if the situation is similar to NGC 7469, the upper limit for the far-infrared luminosity is a third or less of the total far-infrared luminosity emitted by Mrk 231.

4. IRAS F10214+4724

This galaxy at $z = 2.28$, about 17 times farther away than NGC 7469 (5.3 kpc arcsec^{-1}), has been interpreted to be one of the most luminous galaxies in the visible universe ($L \geq 10^{14}\,L_\odot$) in an early super starburst (Downes, Solomon, & Radford 1995; Rowan-Robinson et al. 1993; Scoville et al. 1995). Recent *Hubble Space Telescope* as well as ground-based imaging strongly suggest that the IR source is gravitationally magnified by a foreground galaxy into an arc-like structure and a counter image (Eisenhardt et al. 1996; Broadhurst & Lehár 1995; Graham & Liu 1995). UV and optical rest-frame long-slit spectroscopy of Elston et al. (1994) shows characteristics of an AGN-type object. The integral-field spectroscopic data presented here resolve part of the nuclear structure and show that F10214 is in fact most likely a composite, with an AGN and circumnuclear star formation both contributing to the total luminosity (Kroker et al. 1996).

Figure 4 shows a *3D* spectrum of the nucleus of F10214 spectrally resolving the Hα/[N II] triplet which is redshifted into the K-band. Channel maps in the Hα and [N II] lines show different morphologies: Hα shows a broad and a narrow component and, in addition, narrow-line emission which is significantly extended along the arc. The [N II] emission is more compact with only very faint extensions. The ratio of the compact [N II]/Hα is 1.7, a value typical for AGN, whereas the ratio of the faint extended [N II]/Hα is 0.5, more typical for star-forming regions. From model calculations, Broadhurst & Lehár (1995) estimated gravitational-lensing magnification factors of 50 for the nucleus and 5 for the extended regions of the host galaxy. Taking these corrections into account, we conclude that the intrinsic luminosity of F10214 is dominated by the radiation of a starburst region approximately 1–2 kpc in diameter (Table 1). This starburst produces the extended Hα emission and the far-IR flux, consistent with the detection of extended CO-emission by Downes, Solomon, & Radford (1995). The AGN component only contributes about a third of the total flux within the K-band.

Table 1. Nuclear and Starburst Components of F10214+4724

Property	Nucleus	Starburst
Size R	< 50 pc	~ 1 kpc
$L(\mathrm{H}\alpha)_{obs}/10^9\,L_\odot$	21 ± 4	1.5 ± 5
Extinction correction	8	10–100
Magnification	50–100	5–10
$L_{bol}/L(\mathrm{H}\alpha)$	400–600	200
$L_{bol}/10^9\,L_\odot$	600–1500	300–6000

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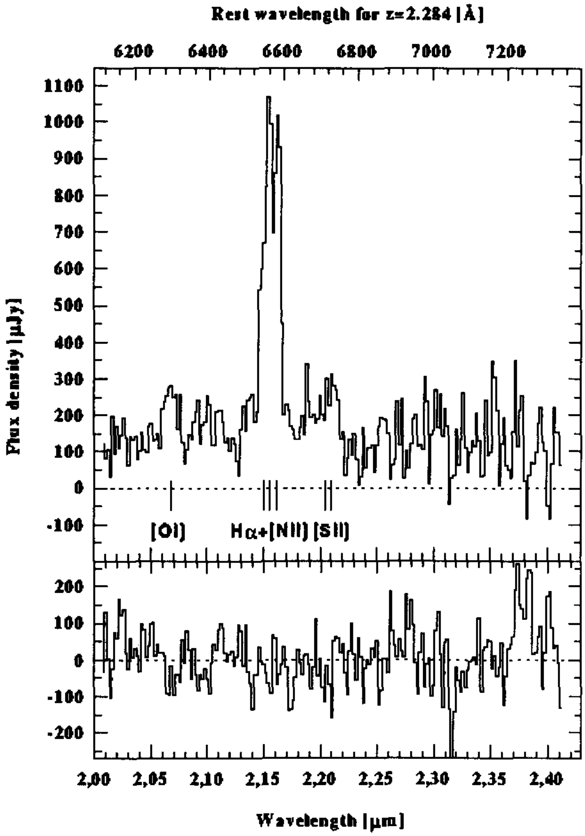

Figure 4. *3D* K-band spectrum of F1021+4724 in a $2''.5$-diameter aperture. The lower spectrum corresponds to a region $4''$ southwest of the source (Kroker et al. 1996).

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5. Circinus

The Circinus galaxy, hosting a Seyfert 2 nucleus surrounded by star-forming regions, is 16 times closer than NGC 7469 (4 Mpc, 20 pc $arcsec^{-1}$). It serves as an example of a nearby AGN where the interaction between the AGN and the star formation can be studied in much greater detail. Our data, presented by Maiolino et al. (this volume), indicate that star formation may occur as close as 10 pc from the nucleus, favoring a possible physical link (e.g., trigger) between the AGN and the star-forming zone.

6. Conclusion

The data that have been presented here show that star formation in the vicinity of AGNs occurs in galaxies covering almost 3 orders of magnitude in total luminosity and at all redshifts. Under conditions of excellent seeing, we spatially resolve the circumnuclear structure even in distant galaxies. We have begun to model successfully the starburst activity and to understand its history and the evolution of the stellar content. The star-formation activity seems to occur even in the immediate vicinity of the AGN on spatial scales of 10 pc.

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