The Interplay among Black Holes, Stars and ISM in Galactic Nuclei
Proceedings IAU Symposium No. 222, 2004
T. Storchi-Bergmann, L. C. Ho & H. R. Schmitt, eds.

DOI: 10.1017/S1743921304001759

Star formation and dynamics in the nuclei of AGN

R. I. Davies[1], **L. J. Tacconi**[1] **and R. Genzel**[1]

[1]Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, 85741, Garching, Germany
email: davies@mpe.mpg.de

Abstract. Using adaptive optics on Keck and the VLT in the H- and K-bands, we have begun a project to probe the dynamics and star formation around AGN on scales of 0.1″. The stellar content of the nucleus is traced through the 2.29 μm CO 2-0 and 1.62 μm CO 6-3 absorption bandheads. These features are directly spatially resolved, allowing us to measure the extent and distribution of the nuclear star forming region. The dynamics are traced through the 2.12 μm H_2 1-0 S(1) and 1.64 μm [FeII] emission lines, as well as stellar absorption features. Matching disk models to the rotation curves at various position angles allows us to determine the mass of the stellar and gas components, and constrain the mass of the central black hole. In this contribution we summarise results for the two type 1 AGN Mkn 231 and NGC 7469.

1. Mkn 231

The ultraluminous infrared galaxy Mkn 231, which at 170 Mpc distance has $L_{\rm bol} \sim 3 \times 10^{12}\,{\rm L}_\odot$, hosts an AGN that, with $M_{\rm B} = -21.7$, is often classed as a QSO. However, it is now clear that a significant fraction of its luminosity infact originates in star formation, making Mkn 231 a key object for investigations into whether or not ULIRGs evolve into QSOs. The structural and kinematic properties of this and other late stage ULIRG mergers have been studied by Genzel *et al.* (2001) to investigate whether they might evolve later into (intermediate mass, L_*) ellipticals; and by Tacconi *et al.* (2002) to test if, once rid of their gas and dust shells, they might be the progenitors of QSOs. As a sample, the ULIRGs appear to have elliptical-like properties: relaxed stellar populations with $r^{1/4}$ radial luminosity profiles, and velocity dispersions of ~180 km s^{-1} with only moderate rotation. Based on numerical simulations of mergers between gas rich spirals, this is what one might expect since most ULIRGs, including Mkn 231, exhibit the huge tidal tails typical of such mergers. However, Mkn 231 presents a puzzle, since its stellar velocity dispersion of 115 km s^{-1} is rather small, yielding both a low bulge mass and a low $M_{\rm BH}$, which results in a highly super-Eddington AGN luminosity. Adaptive optics observations on the Keck II telescope, which are summarised here and described fully in Davies *et al.* (2004b), have resolved this problem.

If the mean stellar type dominating the nuclear stellar H-band continuum does not vary too much, the 1.63 μm CO 6-3 bandhead absorption 'flux' traces the spatial extent of the stars. Fig. 1 (left) shows that this profile is different to the continuum, which has a strong narrow core originating in dust heated by the AGN. Distinguishing between the de Vaucouleurs $r^{1/4}$ and exponential fits to the stellar profile is crucial for our understanding of the geometry of the star forming region. Hence in Fig 1 (right) we plot the logarithm of the profiles as functions of $r^{1/4}$, on which scaling the de Vaucouleurs profile appears as a straight line. It is then clear that an $r^{1/4}$ law does not match the data at larger radii, and that its r_e is inconsistent with the scales on which the star formation is seen. On the other hand, an exponential profile with $r_e \sim 0.2''$ does match the data, indicating that the stars lie in a disk rather than a spheroid.

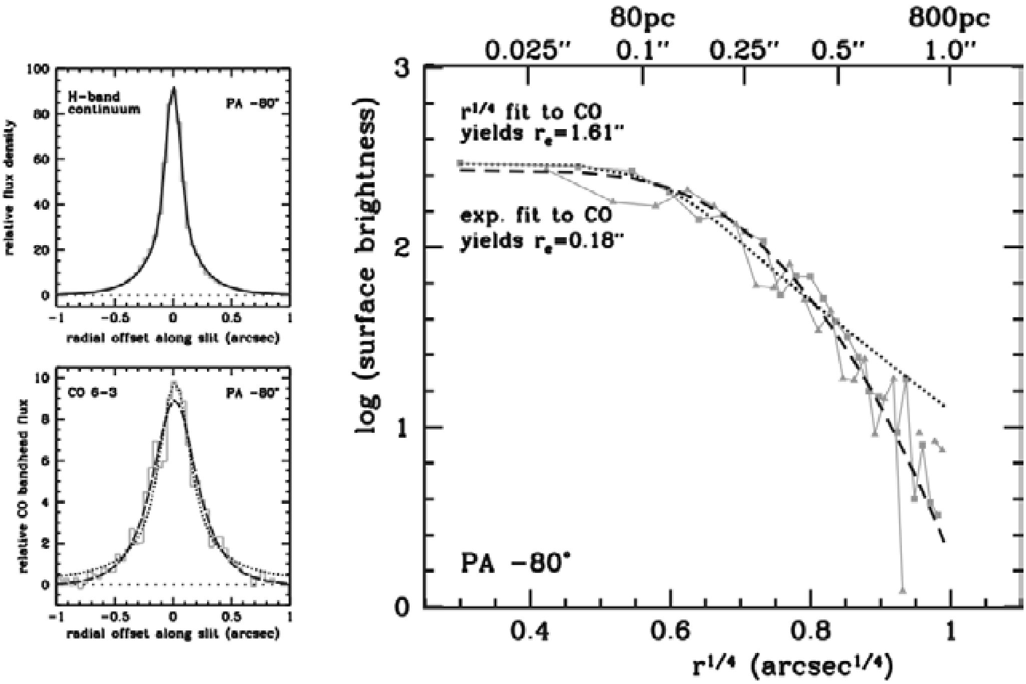

Figure 1. Mkn 231. Left: spatial profiles of the continuum (upper) and CO absorption 'flux' (lower) showing that the nuclear star forming region is resolved. Overplotted in the lower panel are $r^{1/4}$ (dotted) and exponential (dashed) profiles. Right: logarithm of the CO profile as a function of $r^{1/4}$, showing that the exponential (dashed) profile is a better match than the $r^{1/4}$ (dotted), and hence that the stars reside in a disk rather than a spheroid.

A nearly face-on (i=10°) molecular disk is already known to exist in Mkn 231. We need to consider whether our result that the stars lie in the same disk is consistent with the stellar kinematics of Tacconi *et al.* (2002), who found $\sigma = 115\,\mathrm{km\,s^{-1}}$ and $V_{\mathrm{rot}}/\sigma = 0.2$. Using the properties of the molecular disk at $r = 0.6''$ ($V_{\mathrm{rot}} \sin i = 60\,\mathrm{km\,s^{-1}}$, $\mathrm{M_{dyn}} = 12.7 \times 10^9\,\mathrm{M_\odot}$, scale height 23 pc; Downes & Solomon 1998) gives a mean velocity dispersion perpendicular to the disk plane of $80\,\mathrm{km\,s^{-1}}$. Putting in also an exponential profile as above, accounting for seeing, and repeating the observations of Tacconi *et al.* (2002) yields $\sigma = 107\,\mathrm{km\,s^{-1}}$ and an apparent $V_{\mathrm{rot}}/\sigma = 0.3$. This means that a nearly face-on stellar disk can – in the right circumstances – masquerade as a spheroid.

The fraction of H-band light due to stars is found from the equivalent width of the CO 6-3 bandhead, W_{CO}. The stellar luminosity one derives can then be used in starburst models, yielding a minimum mass (occuring when late type supergiants dominate the continuum, at an age of ∼10 Myr) of $1.3 \times 10^9\,\mathrm{M_\odot}$ out to $r = 0.6''$. The upper limit to the age and mass is set by $\mathrm{M_{dyn}}$. At $0.6''$, we find $\mathrm{M_{dyn}} = 6.7 \times 10^9\,\mathrm{M_\odot}$ (half of that derived by Downes & Solomon (1998), since we measure $V_{\mathrm{rot}} \sin i = 40\,\mathrm{km\,s^{-1}}$). Accounting for the gas mass leaves at most $4.3 \times 10^9\,\mathrm{M_\odot}$ of stars. Hence, from starburst models, the maximum age of the stars is 120 Myr. This remarkably young age is supported by other observations of PAH features (Rigopoulou *et al.* 1999), mid infrared emission lines (Genzel *et al.* 1998), the infrared spectral energy distribution (Verma 1999), and the radio continuum (Carilli *et al.* 1998).

Our results show that the stars we see lie in a disk rather than a spheroid, and so σ cannot be used to estimate $\mathrm{M_{BH}}$. Being so young, it is likely that the stars formed *in*

https://doi.org/10.1017/S1743921304001759 Published online by Cambridge University Press

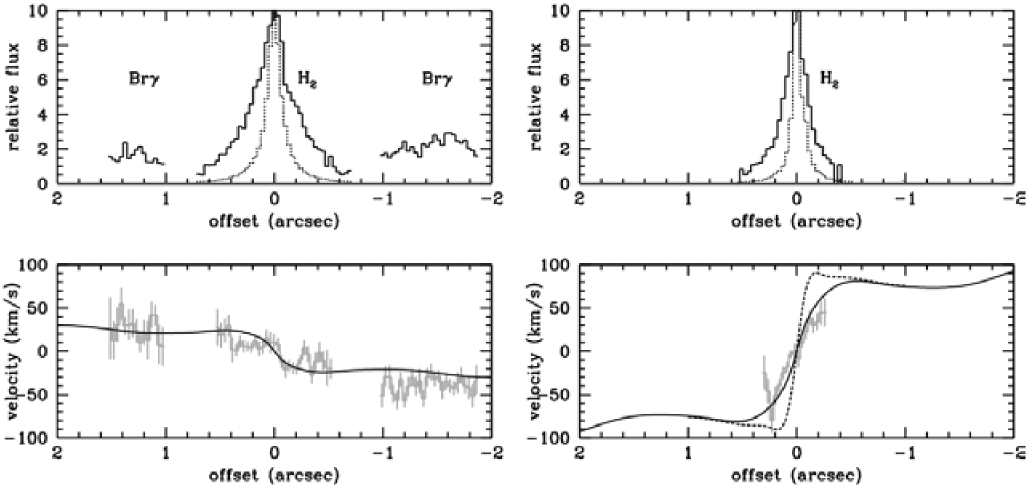

Figure 2. NGC 7469. Spatial (upper) and velocity (lower) profiles at PAs 33° (left) and 100° (right) for K-band emission lines. The continuum is shown in the upper panels (dotted line) for reference. Overplotted in the lower panels are the velocity curves from the mass model, which match the data well and show that on these scales the central mass is not compact (the dotted line in the lower right panel shows how the velocity curve would appear if it were).

situ in the nearly face-on gas disk, which is itself a product of the merger that created Mkn 231.

2. NGC 7469

The Seyfert 1 galaxy NGC 7469, at a distance 66 Mpc, is a luminous infrared source with $L_{\rm bol} \sim 3 \times 10^{11}\,L_\odot$. Much of the interest in the galaxy has been focussed on the circumnuclear ring structure on scales of 1.5–2.5″, which has been observed at many wavelengths. These data suggest that recent star formation in this ring contributes more than half the galaxy's bolometric luminosity. Additionally, up to 1/3 of the K-band continuum within 1″ of the nucleus may also originate in stellar processes (Mazarella *et al.* 1994, Genzel *et al.* 1995). NGC 7469 is therefore a key object for studying the relation between circumnuclear star formation and an AGN, and how gas is driven in to the nucleus to fuel these processes. Bringing together the unique combination of high resolution mm CO 2-1 data from the IRAM Plateau de Bure interferometer and near infrared adaptive optics H_2 1-0 S(1) data from the Keck II telescope, gives us a tool which can probe the distribution and kinematics of the molecular gas across nearly 2 orders of magnitude in spatial scale. Here we summarise our results, which are described fully in Davies *et al.* (2004a).

Our 0.7″ 228 GHz CO 2-1 data of NGC 7469 show a number of distinct components: a broad disk; a ring of molecular clouds at a radius of 2.3″, located outside the well-known ring of star forming knots; a bar or loosely wound spiral arms leading in from the ring; and an extended nucleus which, based also on the AO data, we interpret as a ring at radius 0.2″. An axisymmetric disk model is able to replicate the kinematics of this cold molecular gas, as well as the hot molecular gas traced by the 1-0 S(1) line at much higher spatial resolution. The latter is shown in Fig. 2 which emphasizes the extended nature of the nucleus: if it were compact, the rotation curve would be much steeper than is observed. In contrast to the mass, the 1-0 S(1) flux is compact, indicating that it does not trace the gas distribution. It is likely that the core 1-0 S(1) arises in gas excited by

https://doi.org/10.1017/S1743921304001759 Published online by Cambridge University Press

UV and X-ray irradiation from the AGN, and its distribution depends primarily on the high energy photon density rather than gas density.

Using the 2.29 μm CO 2-0 bandhead we can resolve the nuclear star forming region, which has FWHM 0.22″ and 0.12″ at the 2 PAs, indicating a size scale of ∼40 pc. The fraction of K-band light due to stars is determined from both the slope of the continuum and W_{CO} to be 20–30%. Based on the derived stellar luminosity, starburst models then indicate that the minimum mass of stars within a radius of 0.1″ is 1.5×10^7 $M_\odot$ (occuring if the age is only 10 Myr, when late type supergiants dominate the near infrared stellar continuum). The maximum mass is constrained by M_{dyn} to be 3.5×10^7 $M_\odot$, requiring an age no greater than 60 Myr. Thus, the stars in this cluster are very young, lie predominantly within the molecular gas ring at 0.2″, and account for most of the mass on this scale.

3. Conclusions

We have presented H- and K-band adaptive optics observations which clearly resolve the nuclear star forming regions in the centres of 2 type 1 AGN. Constraining starburst models using the fraction of stellar light determined from W_{CO} and the dynamics measured from the H_2 1-0 S(1) line (and, where possible, stellar features), indicates that the nuclear star forming regions are extremely young and constitute a significant fraction of the total mass on these scales. In Mkn 231 it is likely that the stars have formed in the molecular disk of effective radius 160–200 pc which has resulted from the merger of gas rich spirals; in NGC 7469 the star cluster lies inside a molecular ring of radius 65 pc.

References

Carilli, C., Wrobel, J., & Ulvestad, J. 1998, AJ, 115, 928
Davies, R., Tacconi, L., & Genzel, R. 2004a, ApJ, 602, 148
Davies, R., Tacconi, L., & Genzel, R. 2004b, ApJ, submitted
Downes, D., & Solomon, P. 1998, ApJ, 507, 615
Genzel, R., et al. 1995, ApJ, 444, 129
Genzel, R., et al. 1998, ApJ, 498, 579
Genzel, R., Tacconi, L. J., Rigopoulou, D., Lutz, D., & Tecza, M. 2001, ApJ, 563, 527
Mazzarella, J., Voit, G., Soifer, B., Matthews, K., Graham, J., Armus, L., & Shupe, D. 1994, AJ, 107, 1274
Rigopoulou, D., Spoon, H., Genzel, R., Lutz, D., Moorwood, A., & Tran, Q. 1999, AJ, 118, 2625
Tacconi, L. J., Genzel, R., Lutz, D., Rigopoulou, D., Baker, A. J., Iserlohe, C., & Tecza, M., 2002, ApJ, 580, 73
Verma A. 1999, PhD Thesis, Imperial College, London

https://doi.org/10.1017/S1743921304001759 Published online by Cambridge University Press