A CLOSE LOOK AT STAR FORMATION AROUND ACTIVE GALACTIC NUCLEI

R. I. Davies, F. Mueller Sánchez, R. Genzel, L. J. Tacconi, E. K. S. Hicks, and S. Friedrich
Max Planck Institut für extraterrestrische Physik, D-85741 Garching, Germany

AND

A. Sternberg
School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel

Received 2007 April 4; accepted 2007 August 29

ABSTRACT

We analyze star formation in the nuclei of nine Seyfert galaxies at spatial resolutions down to 0.085″, corresponding to length scales of order 10 pc in most objects. Our data were taken mostly with the near-infrared adaptive optics integral field spectrograph SINFONI. The stellar light profiles typically have size scales of a few tens of parsecs. In two cases there is unambiguous kinematic evidence for stellar disks on these scales. In the nuclear regions there appear to have been recent, but no longer active, starbursts in the last 10–300 Myr. The stellar luminosity is less than a few percent of the AGN in the central 10 pc, whereas on kiloparsec scales the luminosities are comparable. The surface stellar luminosity density follows a similar trend in all the objects, increasing steadily at smaller radii up to ~10^13 L_☉ kpc^{-2} in the central few parsecs, where the mass surface density exceeds 10^4 M_☉ pc^{-2}. The intense starbursts were probably Eddington limited and hence inevitably short lived, implying that the starbursts occur in multiple short bursts. The data hint at a delay of 50–100 Myr between the onset of star formation and subsequent fueling of the black hole. We discuss whether this may be a consequence of the role that stellar ejecta could play in fueling the black hole. While a significant mass is ejected by OB winds and supernovae, their high velocity means that very little of it can be accreted. On the other hand, winds from AGB stars ultimately dominate the total mass loss, and they can also be accreted very efficiently because of their slow speeds.

Subject headings: galaxies: active — galaxies: nuclei — galaxies: Seyfert — galaxies: starburst — infrared: galaxies

1. INTRODUCTION

During recent years there has been increasing evidence for a connection between active galactic nuclei (AGNs) and star formation in the vicinity of the central black holes. This subject forms the central topic of this paper and is discussed in §§ 4 and 5.

A large number of studies have addressed the issue of star formation around AGNs. Those that have probed closest to the nucleus, typically on scales of a few hundred parsecs, have tended to focus on Seyferts, notably Seyfert 2 galaxies, since these are the closest examples (Sarzi et al. 2007; Asari et al. 2007; González Delgado et al. 2001; Gu et al. 2001; Joguet et al. 2001; Storchi-Bergmann et al. 2001; Ivanov et al. 2000). The overall conclusion of these studies is that in 30%–50% of the cases the AGN is associated with young (i.e., age less than a few 100 Myr) star formation. While this certainly implies a link, it does not necessarily imply any causal link between the two phenomena. Instead, it could merely show simply a natural consequence of the fact that both AGNs and starbursts require gas to fuel them, and that in some galaxies this gas has fallen toward the nucleus, due to either an interaction or secular evolution such as bar-driven inflow.

One aspect that must be borne in mind when interpreting such results, and which has been pointed out by Knapen (2004), is the discrepancy in the scales involved. AGN and starburst phenomena occur on different temporal and spatial scales, and observations are sensitive to scales that are different again. For example, star formation has typically been studied on scales of several kilo-parsecs down to a few hundred parsecs. In contrast, accretion of gas onto an AGN will occur on scales much less than 1 pc. Similarly, the shortest star formation timescales that most observations are sensitive to are of order 100 Myr–1 Gyr. On the other hand, in this paper we show that the active phase of star formation close around a black hole is typically rather less than 100 Myr. Correspondingly short accretion timescales for black holes are reflected in the ages of jets, which, for a sample of radio galaxies measured by Machalski et al. (2007), span a range from a few to 100 Myr. In Seyfert galaxies the timescales are even shorter, as typified by NGC 1068, for which Capetti et al. (1999) estimate the age of the jets to be only ~0.1 Myr. That the putative causal connection between AGNs and starbursts might occur on relatively small spatial scales and short timescales can help us to understand why no correlation has been found between AGNs and (circum)nuclear starbursts in general. It is simply that the circumnuclear activity on scales greater than a few hundred parsecs is, in most cases, too far from the AGN to influence it or be strongly influenced by it (e.g., Heckman et al. 1997).

In this paper we redress this imbalance. While the optical spectroscopy pursued by many authors allows a detailed fitting of templates and models to the stellar features, we also make use of established star formation diagnostics and interpret them using starburst population synthesis models. Observing at near-infrared wavelengths has brought two important advantages. The optical depth is 10 times less than at optical wavelengths, and thus our data are less prone to the effects of extinction, which can be significant in AGNs. In addition, we have employed adaptive optics (AO) to reach spatial resolutions of 0.1''–0.2'', bringing us closer to the nucleus. Applying these techniques, we have already analyzed the properties of the nuclear star formation in a few objects.
cuss the implications of nuclear starbursts on the starburst-AGN relationship, there is clear broad (FWHM > 0.15") emission in three AGNs that are not usually classified as Seyfert 1. Top: NGC 3227 (0.25" aperture); middle: IRAS 05189–2524 (1" aperture); bottom: NGC 2992 (0.5" aperture). The most prominent emission and absorption features are marked.

(Davies et al. 2004a, 2004b, 2006; Mueller Sánchez et al. 2006). Here we bring those data together with new data on five additional objects. Our sample enables us to probe star formation in AGNs from radii of 1 kpc down to less than 10 pc. Our aim is to ascertain whether there is evidence for star formation on the smallest scales we can reach and, if so, to constrain its star formation history. Ultimately, we look at whether there are indications that the nuclear starbursts and AGNs are mutually influencing each other.

In § 2 we describe the sample selection, observations, data reduction, PSF estimation, and extraction of the emission- and absorption-line morphologies and kinematics. In § 3 we discuss the observational diagnostics and modeling tools. Brief analyses of the relevant facets of our new data for the individual objects are provided in the Appendix, where we also summarize results of our previously published data, reassessing them where necessary to ensure that all objects are analyzed in a consistent manner. The primary aims of our paper are addressed in § 4 and 5. In § 4 we discuss global results concerning the existence and recent history of nuclear star formation for our whole sample. In § 5 we discuss the implications of nuclear starbursts on the starburst-AGN connection. Finally, we present our conclusions in § 6.

2. SAMPLE, OBSERVATIONS, DATA PROCESSING

2.1. Sample Selection

The AGNs discussed in this paper form a rather heterogeneous group. They include type 1 and type 2 Seyferts, ultraluminous infrared galaxies (ULIRGs), and even a QSO and do not constitute a complete sample. In order to maximize the size of the sample, we have combined objects on which we have already published AO near-infrared spectra with new observations of additional targets.

Source selection was driven largely by technical considerations for the AO system, namely, having a nucleus bright and compact enough to allow a good AO correction. This is actually a strength since it means that seven of the nine AGNs are in fact broad-line objects, as given either by the standard type 1 classification or because there is clear broad (FWHM > 1000 km s$^{-1}$) Br$\gamma$ emission in our spectra. Figure 1 shows broad Br$\gamma$ in K-band spectra of three AGNs that are not usually classified as broad-line galaxies. This is in contrast to most other samples of AGNs for which star formation has been studied in detail and avoids any bias that might arise from selecting only type 2 Seyferts. That there may be a bias arises from the increasing evidence that the obscuration in perhaps half of type 2 AGNs lies at kiloparsec scales rather than in the nucleus, which may be caused by spatially extended star formation in the galaxy disk (Brand et al. 2007; Martinez-Sansigre et al. 2006; Rigby et al. 2006). Such AGNs do not fit easily into the standard unification scheme (and perhaps should not really be considered type 2 objects). Because broad lines can be seen in the infrared, we know that we are seeing down to the nuclear region and hence our results are not subject to any effects that this might otherwise introduce.

It is exactly broad-line AGNs for which little is known about the nuclear star formation because the glare of the AGN swamps any surrounding stellar light in the central arcsecond. As a result, most studies addressing star formation close to AGNs have focused on type 2 Seyferts. AO makes it possible to confine much of the AGN’s light into a very compact region and to resolve the stellar continuum around it. The use of AO does give rise to one difficulty when attempting to quantify the results in a uniform way, due to the different resolutions achieved, which is a combination of both the distance to each object (i.e., target selection) and the AO performance. As a result, the standard deviation around the logarithmic mean resolution of our sample (excluding NGC 2992; see the Appendix) of 22 pc is a factor of 3. However, this has enabled us to study the centers of AGNs across nearly 3 orders of magnitude in spatial scale, from 1 kpc in the more distant objects to only a few parsecs in the nearby objects with the best AO correction.

2.2. Observations and Reduction

A summary of our observations is given in Table 1, and the basic data for the objects in Table 2. A description of observations and processing of the new data is given below.

Data for IRAS 05189–2524 and NGC 1068 were taken in 2002 December at the VLT with NACO, an AO near-infrared camera and long-slit spectrograph (Lenzen et al. 2003; Rouset...
Table 2

| Object          | Radius (arcsec) | Radius (pc) | log (L* / L_☉) | log (M_dyn / M_☉) | Σ_dyn (M_☉ pc^-2) | V_Br (km s^-1) | M_dyn / L_☉ (M_☉ L_☉^-1) | L_{rest, 4000} / L_☉ (yr^-1 L_☉^-1) | Age (Myr) | (SFR) (M_☉ yr^-1 kpc^-2) |
|-----------------|-----------------|-------------|-----------------|-------------------|-------------------|----------------|-------------------------|-----------------------------------|-----------|--------------------------|
| Mrk 231         | 0.6             | 480         | 9.3             | 9.8               | 0.9               | ...            | 3.1                     | 20                               | 120-250   | 25-50                    |
| NGC 7469        | 0.4             | 128         | 8.5             | 8.7               | 1.0               | 11             | 1.6                     | 3                                | 110-190   | 50-100                   |
| Circinus        | 0.4             | 8           | 6.2             | 7.5               | 17                | 30             | 23                      | 1.5                               | 80        | ~70                      |
| NGC 3227        | 0.4             | 32          | 7.8             | 8.0               | 3.7               | 4              | 1.9                     | 2.2                               | 40        | ~380                     |
| IRAS 05189-2524 | 0.55            | 450         | 9.3             | ...               | ...               | 4              | ...                     | 5                                | 50-100    | 30-70                    |
| NGC 2992        | 0.4             | 64          | 7.5             | ...               | ...               | <12            | ...                     | 1                                | ...       | ...                     |
| NGC 1097        | 0.25            | 22          | 6.7             | 8.2               | 1.3               | 1              | 4.5                     | 1.4                               | 8         | ~80                      |
| NGC 1068        | 0.5             | 35          | 7.6             | 8.1               | 3.4               | 4              | 3.0                     | <20                               | 200-300   | 90-170                   |
| NGC 3783        | 0.3             | 60          | 7.5             | 7.3               | 0.2               | <30            | 0.6                     | 2                                | 50-70     | 30-60                    |

Notes.—The methods used to measure these quantities (within the radii given) are described in § 3. Specific issues associated with individual objects are discussed in the Appendix.

a M_dyn depends strongly on even small changes to the inclination; here it is given for i = 10°. Correcting M_dyn for an estimate of the gas mass given in Downes & Solomon (1998) yields M/L_e = 2.3 M_☉ L_e^-1.

b The best star formation models indicate that M/L_e is much less than the limit given here using the dynamical mass.

c It is likely that much of the narrow Brγ in the nuclear region here is associated with an ionization cone. In addition, the high stellar velocity dispersion, even on the smallest scales we have been able to measure, suggests that the K-band light is dominated by the bulge.

d Correcting V_Br for the old stellar population would probably yield a value in the range 2-5 Å. Even on this scale the dynamical mass is dominated by the supermassive black hole. Both Σ_dyn and M/L_e are estimated after subtracting M_HI.

e Much of the Brγ here is outflowing and hence associated with the AGN. M_dyn is derived from gas kinematics as described in the text. Both Σ_dyn and M/L_e are estimated after subtracting M_HI.

Data for NGC 7469, NGC 2992, NGC 1097, NGC 1068, and NGC 3783 were taken during 2004–2005 at the VLT with SINFONI, an AO near-infrared integral field spectrograph (Eisenhauer et al. 2003; Bonnet et al. 2004). Data were taken with various gratings covering the H and K bands either separately (R ~ 4000) or together (R ~ 1500). The pixel scales were 0.125" × 0.25" or 0.05" × 0.1", depending on the trade-offs between field of view, spatial resolution, and signal-to-noise ratio. Individual exposure times are in the range 50–300 s depending on the object brightness. Object frames were interspersed with sky frames, usually using the sequence O-S-O-O-S-O, to facilitate background subtraction. The data were processed using the dedicated SPRED software package (Abuter et al. 2006), which provides similar processing to that for long-slit data but with the added ability to reconstruct the data cube. The data processing steps are as follows. The object frames are preprocessed by subtracting sky frames, flat-fielding, and correcting bad pixels (which are identified from dark frames and the flat field). The wave map is generated, and edges and curvature of the slitlets are traced, all from the arc lamp frame. The arc lamp frame is then reconstructed into a cube, which is checked to ensure that the calibration is good. The preprocessed object frames are then also reconstructed into cubes, spatially shifted to align them using the bright nucleus as a reference, and combined. In some cases the final cube was spatially smoothed using a 3 × 3 median filter. Estimation of the spatial resolution (see below) was always performed after this stage.

In some cases, the strong near-infrared OH lines did not subtract well. With longer exposure times this is to be expected since the timescale for variation of the OH is only 1–2 minutes. If visual inspection of the reconstructed cubes showed signs of over- or undersubtraction of the OH lines, these cubes were reprocessed using the method described in Davies (2007a).

Standard-star frames are similarly reconstructed into cubes. Telluric correction and flux calibration were performed using B stars (K band) or G2 V stars (H band). In addition, flux calibration was cross-checked in 3" apertures using Two Micron All Sky Survey (2MASS) data and in smaller 1"–3" apertures using broadband imaging from NACO or Hubble Space Telescope NICMOS. Agreement between cubes with different pixel scales, and also with the external data, was consistent to typically 20%.

2.3. PSF Estimation

There are a multitude of ways to derive the point-spread function (PSF) from AO data, five of which are described in Davies (2007b). With AGNs, it is usually possible to estimate the PSF from the science data themselves, removing any uncertainty about spatial and temporal variations of the PSF due to atmospheric effects. Typically one or both of the following methods are employed on the new data presented here. If a broad emission line is detected, this will always yield a measure of the PSF since the broad-line region (BLR) of Seyfert galaxies has a diameter that can be measured in light-days. Alternatively, the nonstellar continuum will provide a sufficiently good approximation in all but the nearest AGNs since at near-infrared wavelengths it is expected to originate from a region no more than 1–2 pc across.

In every case we have fitted an analytical function to the PSF. Since the Strehl ratio achieved is relatively low, even a Gaussian is a good representation. We have used a Moffat function, which achieves a better fit because it also matches the rather broad wings that are a characteristic of partial AO correction. The PSF measured for NGC 3227, which is shown in Figure 1 of Davies et al. (2006), can be considered typical. If one applies the concept of "core plus halo" to this PSF, then the Gaussian fit would represent just the core while the Moffat fit would represent the entire core plus halo. Integrating both of these functions indicates that...
about 75% of the flux is within the core, and it is thus this component that dominates the PSF. In this paper, a more exact representation of the PSF is not needed since we have not performed a detailed kinematic analysis, and we have simply used the Moffat function to derive an FWHM for the spatial resolution. The resolutions achieved are listed in Table 1.

### 2.4. Emission/Absorption-Line Characterization

The two-dimensional (2D) distribution of emission and absorption features has been found by fitting a function to the continuum-subtracted spectral profile at each spatial position in the data cube. The function was a convolution of a Gaussian with a spectrally unresolved template profile: in the case of emission lines it was an OH sky emission line, and for stellar absorption features we made use of template stars observed in the same configuration (pixel scale and grism). A minimization was performed in which the parameters of the Gaussian were adjusted until the convolved profile best matched the data. During the minimization, pixels in the data that consistently deviated strongly from the data were rejected. The uncertainties were bootstrapped using Monte Carlo techniques, assuming that the noise is uncorrelated and the intrinsic profile is well represented by a Gaussian. The method involves adding a Gaussian with the derived properties to a spectral segment that exhibits the same noise statistics as the data, and refitting the result to yield a new set of Gaussian parameters. After repeating this 100 times, the standard deviation of the center and dispersion were used as the uncertainties for the velocity and line width.

The kinematics was further processed using kinemetry (Krajnović et al. 2006). This is a parameterization (i.e., a mathematical rather than a physical model) of the 2D field. As such, beam smearing is not a relevant issue to kinemetry, which yields an analytical expression for the observed data. Of course, when the coefficients of this expression are interpreted or used to constrain a physical model, then beam smearing should be considered. Mathematically, the kinemetry procedure fits the data with a linear sum of sines and cosines with various angular scalings around ellipses at each radius. We have used it for three purposes: to determine the best position angle and axis ratio for the velocity field, to remove high-order noise from the raw kinematic extraction, and to recover the velocity and dispersion radial profiles. In all of the cases considered here, the kinematic center of the velocity field was assumed to be coincident with the peak of the nonstellar continuum. In addition, the uniformity of the velocity field permitted us to make the simplifying assumption of a single position angle and axis ratio; i.e., there is no evidence for warps or twisted velocity contours. We then derived the position angle and inclination of the disk by minimizing the A1 and B3 parameters, respectively (for a description of these see Krajnović et al. 2006). The rotation curves were recovered by correcting the measured velocity profile for inclination. We have assumed throughout the paper that the dispersion is isotropic, and hence no inclination correction was applied to the dispersion that was measured.

The innermost parts of the kinematics derived as above are of course still affected by beam smearing. In general, the central dispersion cannot necessarily be taken at face value since it may be either artificially increased by any component of rotation included within the beam size or decreased if neighboring regions within the beam have a lower dispersion. In the galaxies we have studied, there are two aspects that mitigate this uncertainty: the rotation speed in the central region is much less than the dispersion and so will not significantly alter it; and when estimating the central value, we consider the trend of the dispersion from large radii, where the effect of the beam is small, to the center. For the basic analyses performed here, we have therefore adopted the central dispersion at face value. More detailed physical models for the nuclear disks, which properly account for the effects of beam smearing, will be presented in future publications. Lastly, we emphasize that the impact of the finite beam size on the derived rotation curve does not affect our measurement of the dynamical mass. The reason is that, for all the dynamical mass estimates we make, the mass is estimated at a radius much larger than the FWHM of the PSF, as can be seen in the relevant figures.

### 3. Quantifying the Star Formation

In this section we describe the tools of the trade used to analyze the data, which led us to the global results presented in § 4. Specific details and analyses for individual objects can be found in the Appendix. We use the same methods and tools for all the objects to ensure that all the data are analyzed in a consistent manner.

Perhaps the most important issue is how to isolate the stellar continuum, which is itself a powerful diagnostic. In addition, we use three standard and independent diagnostics to quantify the star formation history and intensity in the nuclei of these AGNs. These are the Brγ equivalent width, supernova rate, and mass-to-light ratio. Much of the discussion concerns how we take into account these diagnostics.
account the contribution of the AGN when quantifying these parameters. We also consider what impact an incorrect compensation could have on interpretation of the diagnostics.

We model these observational diagnostics using the stellar population and spectral synthesis code STARS (e.g., Sternberg 1998; Sternberg et al. 2003; Förster Schreiber et al. 2003; Davies et al. 2003, 2005). This code calculates the distribution of stars in the Hertzsprung-Russell diagram as a function of age for an assumed star formation history. We usually assume an exponentially decaying star formation rate, which has an associated timescale \( \tau_{\text{SF}} \). Spectral properties of the cluster are then computed given the star formation history and age. For a stellar continuum diluted by additional nonstellar emission, the fraction of stellar light is understood because these are selected to have bright emission lines and hence are strongly biased toward young stellar ages, often corresponding to the maximum depth of the stellar features that occurs at 10 Myr due to the late-type supergiant population. It may be this bias for galaxies selected as “starbursts” and the similarity of the CO depth for starbursts of all other ages that led Ivanov et al. (2000) to conclude that there is no evidence for strong starbursts in Seyfert 2 galaxies. Similarly, an estimate of the dilution can be found from the Na\( i \) 2.206 \( \mu \)m line. Figure 7 of Davies et al. (2005) shows that for nearly all star formation histories the value \( W_{\text{Na}i} \), remains in the range 2–3 \( \AA \).

Our conclusion here is that within a reasonable uncertainty of ±20% (see Fig. 2), one can assume that the intrinsic equivalent width of the absorption (most notably CO) features of any stellar population that contains late-type stars is independent of the star formation history and age. For a stellar continuum diluted by additional nonstellar emission, the fraction of stellar light is

\[
I_{\text{stellar}} = \frac{W_{\text{obs}}}{W_{\text{int}}},
\]

where \( W_{\text{obs}} \) and \( W_{\text{int}} \) are the observed and intrinsic equivalent widths of the CO features discussed above. Thus, we are able to correct the observed continuum magnitude for the contribution associated with the AGN.

3.2. Stellar Color and Luminosity

Our data cover both the \( H \) and \( K \) bands, hence the reason for using both \( W_{\text{CO}(6-3)} \) and \( W_{\text{CO}(2-0)} \). In order to homogenize the data set, we need to convert \( H \)-band stellar magnitudes to \( K \) band. The STARS computation in Figure 3 shows that this conversion is also independent of the star formation history, being close to \( H - K = 0.15 \) mag (no extinction) for all timescales and ages. This result is supported empirically by photometry of elliptical and spiral galaxies performed by Glass (1984). For ellipticals \( H-K \sim 0.2-0.25 \), and for spirals \( H-K \sim 0.2-0.3 \). Some of

![Graphs showing H-K color of star clusters with different star formation timescales and ages, as calculated by STARS. Right: Ratio of bolometric to K-band luminosity.](image-url)
the difference between the data and models could be due to extinction since \( H - K = (H - K)_0 + (A_H - A_K) \), and for \( A_Y = 1 \), \( A_H - A_K = 0.08 \). However, at the level of precision required here, the 5%–10% difference between model and data can be considered negligible.

To convert from absolute magnitude to luminosity, we use the relation

\[
M_K = -0.33 - 2.5 \log L_K,
\]

where \( L_K \) is the total luminosity in the 1.9–2.5 \( \mu \)m band in units of bolometric solar luminosity (1 \( L_\odot = 3.8 \times 10^{26} \) W), and as such different from the other frequently used monochromatic definition with units of the solar \( K \)-band luminosity density (2.15 \( \times 10^{25} \) W \( \mu \)m\(^{-1} \)). We then use STARS to estimate the bolometric stellar luminosity \( L_{\text{bol}} \). The relation between \( L_{\text{bol}} \) and \( L_K \) is shown in the right panel of Figure 3. The dimensionless ratio \( L_{\text{bol}}/L_K \) depends on the age and the exponential decay timescale of the star formation. However, the range spanned is only 20–200 for ages greater than 10 Myr. Thus, even if the star formation history cannot be constrained, a conversion ratio of \( L_{\text{bol}}/L_K \sim 60 \) will have an associated uncertainty of only 0.3 dex. In general, we are able to apply constraints on the star formation age, and so our errors will be accordingly smaller.

3.3. Specific Star Formation Diagnostics

Graphs showing how the diagnostics vary with age and star formation timescale are shown in Figure 4.

3.3.1. Br\(_γ\) Equivalent Width

Once the stellar continuum luminosity is known, an upper limit to the equivalent width of \( \text{Br}_\gamma \) associated with star formation can be found from the narrow \( \text{Br}_\gamma \) line flux. In some cases it is possible to estimate what fraction of the narrow \( \text{Br}_\gamma \) might be associated with the AGN. This can be done morphologically (for example, if the line emission is extended along the galaxy’s minor axis) and/or kinematically (for example, if the line shows regions that are broader, perhaps with FWHM a few hundred kilometers per second, suggestive of outflow). Even if accounting for the AGN contribution is not possible, one may be able to set interesting upper limits or even rule out continuous star formation scenarios and put a constraint on the time since the star formation was active. This can be seen in the left panel of Figure 4, which shows, for example, that for ages less than 10\(^9\) yr, continuous star formation scenarios will always have \( W_{\text{Br}_\gamma} > 12 \) \( \AA \).

3.3.2. Supernova Rate

We estimate the Type II (core collapse) supernova rate \( \nu_{\text{SN}} \) from the radio continuum using the relation (Condon 1992)

\[
L_N (\text{W Hz}^{-1}) = 1.3 \times 10^{23} \nu^{-\alpha} (\text{GHz}) \nu_{\text{SN}} (\text{yr}^{-1}),
\]

where \( L_N \) is the nonthermal radio continuum luminosity, \( \nu \) is frequency of the observation, and \( \alpha \sim 0.8 \) is the spectral index of the nonthermal continuum. This relation was derived for Galactic supernova remnants, but a similar one, differing only in having a coefficient of 1.1 \( \times 10^{23} \), was derived by Huang et al. (1994) for M82. For the 5 GHz nonthermal radio continuum luminosity of Arp 220 (176 mJy; Anantharamaiah et al. 2000) it would lead to a supernova rate of 2.9 yr\(^{-1} \), comfortably within the 1.75–3.5 yr\(^{-1} \) range estimated by Smith et al. (1998) based on the detection of individual luminous radio supernovae. This, therefore, seems a reasonable relation to apply to starbursts.

We have to be careful, however, to take into account any contribution from the AGN to the radio continuum. Our premise for the nuclei of Seyfert galaxies is that if the nuclear radio continuum is spatially resolved (i.e., it has a low brightness temperature) and does not have the morphology of a jet, it is likely to originate in extended star formation. At the spatial scales of a few parsecs or more that we can resolve, emission from the AGN will be very compact. As a result, we can use the peak surface brightness to estimate the maximum (unresolved) contribution from an AGN. Wherever possible, we use radio continuum observations at a comparable resolution to our data to derive the extended emission and observations at higher resolution to estimate the AGN contribution. Details of the data used in each case are given in the relevant subsections for each object in the Appendix. In addition, we exclude any emission obviously associated with jets, for example, as in NGC 1068.

To use \( \nu_{\text{SN}} \) as a diagnostic, we normalize it with respect to the stellar \( K \)-band luminosity. This gives the ratio \( 10^{10} \nu_{\text{SN}}/L_K \), for which STARS output is drawn in Figure 4.

3.3.3. Mass-to-Light Ratio

Models indicate that the ratio \( M/L_K \) of the stellar mass to \( K \)-band luminosity should be an excellent diagnostic since, for
ages greater than 10 Myr, it increases monotonically with age as shown in Figure 4.

However, in practice, estimating the stellar mass is not entirely straightforward. In many cases it is only practicable to derive the dynamical mass. It may be possible to estimate and hence correct for the molecular gas mass based on millimeter CO maps, but these are scarce at sufficiently high spatial resolution and are associated with their own CO-to-H$_2$ conversion uncertainties. We also note that it is often not possible to separate the “old” and “young” stellar populations. The best one can do is estimate the overall mass-to-light ratio and argue that this is an upper limit to the true ratio for the young population. While there inevitably remains uncertainty on the true ratio, the limit is often sufficient to apply useful constraints on the age of the young population.

Our estimates of the dynamical mass are based wherever possible on the stellar kinematics, since the gas kinematics can be perturbed by warps, shocks, and outflows. We begin by estimating the simple Keplerian mass assuming that the stars are supported by ordered rotation at velocity $V_{\text{rot}} = V_{\text{obs}}/\sin i$ in a thin plane. However, the stellar kinematics in all the galaxies exhibits a significant velocity dispersion indicating that a considerable mass is supported by random rather than ordered motions. Thus, the simple Keplerian mass is very much an underestimate, and any estimate of the actual mass is associated with large uncertainties; see, for example, Bender et al. (1992), who derive masses of spheroidal systems. As stated in § 2, we assume that the random motions are isotropic. Our relation for estimating the mass enclosed within a radius $R$ is then

$$M = \frac{(V_{\text{rot}}^2 + 3\sigma^2)R}{G},$$

where $\sigma$ is the observed one-dimensional velocity dispersion.

We note that when taking rotation into account in estimating the masses of spheroids with various density profiles, Bender et al. (1992) also use a factor of 3 between the $V$ and $\sigma$ terms in their Appendix B. Despite the complexities involved, within the unavoidable uncertainties (a factor of 2–3), their relation gives the same mass as that above. Although this uncertainty appears to be quite large, it does not impact the results and conclusions in this paper since we are concerned primarily with order-of-magnitude estimates when considering mass surface densities.

### 4. PROPERTIES OF NUCLEAR STAR FORMATION

In the following section we bring together the individual results (detailed in the Appendix) to form a global picture. It is possible to do this because all the data have been analyzed in a consistent manner, using the tools described in § 3 to compare in each object the same diagnostics to the same set of stellar evolutionary synthesis models.

We note that the discussion that follows is based on results for eight of the AGNs we have observed. As explained in the Appendix, we exclude NGC 2992 because we are not able to put reliable constraints on the properties of the nuclear star formation. Despite this, there are indications that at higher spatial resolution one should expect to find a distinct nuclear stellar population as has been seen in other AGNs.

**Size scale.—**Tracing the stellar features rather than the broad-band continuum, we have in all cases resolved a stellar population in the nucleus close around the AGN. While this should not be unexpected if the stellar distribution follows a smooth $r^{1/4}$ or exponential profile, we have in several cases been able to show that on scales of <50 pc there is in fact an excess above what one

### TABLE 3

**SUMMARY OF BASIC DATA FOR AGNs**

| Object       | Classification$^a$ | Distance (Mpc) | log ($L_{\text{bol}}/L_\odot$)$^b$ | log ($M_{\text{BH}}/M_\odot$) | References for $M_{\text{BH}}$ |
|--------------|--------------------|----------------|----------------------------------|-------------------------------|--------------------------------|
| Mrk 231      | ULIRG, Sy1, QSO    | 170            | 12.5                             | 7.2                           | 1                              |
| NGC 7469     | Sy1                | 66             | 11.5                             | 7.0                           | 2                              |
| Circinus     | Sy2                | 4              | 10.2                             | 6.2                           | 3                              |
| NGC 3227     | Sy1                | 17             | 10.2                             | 7.3                           | 4                              |
| IRAS 05189−2524 | ULIRG, Sy1       | 170            | 12.1                             | 7.5                           | 1                              |
| NGC 2992     | Sy1                | 33             | 10.7                             | 7.7                           | 5                              |
| NGC 1097     | LINER, Sy1         | 18             | 10.9                             | 8.1                           | 6                              |
| NGC 1068     | Sy2                | 14             | 11.5                             | 6.9                           | 7                              |
| NGC 3783     | Sy1                | 42             | 10.8                             | 7.5                           | 2                              |

$^a$ Classifications are taken primarily from the NASA/IPAC Extragalactic Database. In addition, we have labeled as Seyfert 1 those for which we have observed broad (i.e., FWHM $>$ 1000 km $s^{-1}$) Br$\gamma$; see also Fig. 1.

$^b$ Calculated in the range 8–1000 $\mu$m from the IRAS 12–100 $\mu$m flux densities, with an additional correction for optical and near-infrared luminosity in cases where appropriate.

**References.—**(1) Dasyra et al. 2006; (2) Peterson et al. 2004; (3) Greenhill et al. 2003; (4) Davies et al. 2006; (5) Woo & Urry 2002; (6) Lewis & Eracleous 2006; (7) Lodato & Bertin 2003.
would expect from these profiles. This suggests that in general we are probing an inner star-forming component.

Figure 5 shows normalized azimuthally averaged stellar luminosity profiles for the AGN. These have not been corrected for a possible old underlying population, nor has any deconvolution with the PSF been performed. Nevertheless, it is still clear that the stellar intensity increases very steeply toward the nucleus. In six of the eight galaxies shown, the half-width at half-maximum is less than 50 pc. The remaining two galaxies are the most distant in the sample, and the spatial resolution achieved does not permit a size measurement on these scales. We may conclude that the physical radial size scale of the nuclear star-forming regions in Seyfert galaxies does not typically exceed 50 pc.

Stellar age.—For eight of the AGNs studied here, we have been able to use classical star formation diagnostics based on line and continuum fluxes, as well as kinematics to constrain the ages of the inner star-forming regions. The resulting ages should be considered “characteristic,” since in many cases there may simultaneously be two or more stellar populations that are not coeval. For example, if a bulge population exists on these small spatial scales, it was not usually possible to account for the contamination it would introduce. While this would have little effect on $W_{\text{Br}\alpha}$, it could impact $M/L_{\text{K}}$ more strongly, increasing the inferred age. The ages we find lie in the range 10–300 Myr, compelling evidence that it is common for there to be relatively young star clusters close around AGNs.

Intriguingly, we also find rather low values of $W_{\text{Br}\alpha}$: typically $W_{\text{Br}\alpha} \lesssim 10$ Å (see Table 3). This indicates directly that there is currently little or no ongoing star formation. Coupled with the relatively young ages, we conclude that the star formation episodes are short lived. One may speculate then that the star formation is episodic, recurring in short bursts. The scale of the bursts and time interval between them would certainly have an impact on the fraction of Seyfert nuclei in which observational programs are able to find evidence for recent star formation.

Nuclear stellar disks.—The first evidence for nuclear stellar disks came from seeing-limited optical spectroscopy, for which a slight reduction in $\sigma_*$ was seen for some spiral galaxies (Emsellem et al. 2001; Márquez et al. 2003; Shapiro et al. 2003). Furthermore, there are now a growing number of spiral galaxies (more than 30) in which the phenomenon has been observed, suggesting that they might occur in 30% or more of disk galaxies (Emsellem 2006). The $\sigma_*$ drop has been interpreted by Emsellem et al. (2001) as arising from a young stellar population that is born from a dynamically cold gas component, and which makes a significant contribution to the total luminosity. This appears to be borne out by $N$-body and smoothed particle hydrodynamics simulations of isolated galaxies (Wozniak et al. 2003), which suggest that although the entire central system will slowly heat up with time, the $\sigma_*$ drop can last for at least several hundred million years. Indeed, preliminary analysis of optical integral field data for NGC 3623 suggests that the stellar population responsible for the $\sigma_*$ drop cannot be younger than 1 Gyr (Emsellem 2006a).

Our results provide strong support for the nuclear disk interpretation. In previous work (Davies et al. 2006; Mueller Sánchez et al. 2006), we had argued that in both Circinus and NGC 3227 the inner distributions were disklike, albeit thickened. We have now found much more direct evidence for this phenomenon in NGC 1097 and NGC 1068. In both of these galaxies, we have spatially resolved a $\sigma_*$ drop and an excess stellar continuum over the same size scales. In NGC 1097 this size was $\approx 0.5''$, corresponding to about 40 pc. For NGC 1068 these effects were measured out to $\approx 1''$, equivalent to 70 pc. These are not the scale lengths of the disks, but simply the maximum radius to which we can detect them. In both cases the mean mass surface densities are of order $\Sigma = (1-3) \times 10^4 M_\odot$ pc$^{-2}$. For an infinitely large thin self-gravitating stellar disk, one can use the expression $\Sigma^2 = 2\pi G\Sigma_0$ to estimate the scale height. Although this may not be entirely appropriate, we use it here to obtain a rough approximation to the scale heights, which are $5-20$ pc. Thus, while the disks appear to be flattened, they should still be considered thick since the radial extent is only a few times the scale height.

The impact of nuclear starbursts on the central light profile of galaxies was considered theoretically more than a decade ago by Mihos & Hernquist (1994). They performed numerical simulations of galaxy mergers to study the mass and luminosity profiles of the remnants, taking gas into account, and estimating the star formation rate using a modified Schmidt law. They found that there should be a starburst in the nucleus that would give rise to an excess stellar continuum above the $r^{1/4}$ profile of the older stars in the merged system. Several years ago, compact nuclei were found to be present in a significant fraction of spiral galaxies (Balcaps et al. 2003), as well as Coma Cluster dwarf ellipticals (Graham & Guzman 2003). More recently, nuclei with a median half-light radius of 4.2 pc have been found in the majority of early-type members of the Virgo Cluster (Côté et al. 2006) and traced out to $\approx 1''$, equivalent to $\approx 100$ pc, in some of the “wet” merger remnants in that cluster (Kormendy 2006). While the nuclear starbursts in the latter cases are caused by a merger event, whereas those we are studying arise from secular evolution as gas from the galaxy disk accretes in the nucleus, there appear to be many parallels in the phenomenology of the resulting starbursts.

Star formation rate.—It is possible to estimate the bolometric luminosity $L_{\text{bol}}$ of the stars from their K-band luminosity $L_K$ even if one knows nothing about the star formation history. As discussed in §3, this would result in an uncertainty of about a factor of 3. The diagnostics in Table 3 and discussions in the Appendix enable us to apply some constraints to the characteristic age of the star formation. Because continuous star formation is ruled out by the low $W_{\text{Br}\alpha}$, we have assumed exponential decay timescales of $\tau_{\text{SF}} = 10-100$ Myr. We have then used STARS to estimate the average star formation rates. In order to allow a meaningful comparison between the objects, the rates have been normalized to the same area of 1 kpc$^2$. These are the rates given in Table 3. They are calculated simply as the mass of stars produced divided by the entire time since the star-forming episode began. Because $\tau_{\text{SF}}$ is shorter than the age, the average includes both active and non-active phases of the starburst. Indeed, for $\tau_{\text{SF}} = 10$ Myr one would expect the star formation rate during the active phases to be at least a factor of a few, and perhaps an order of magnitude, greater. The table shows that on scales of a few hundred parsecs one might expect a few times $\sqrt{10} M_\odot$ yr$^{-1}$ kpc$^{-2}$, while on scales of a few tens of parsecs mean rates reach $\sim 100 M_\odot$ yr$^{-1}$ kpc$^{-2}$ should not be unexpected, and correspondingly higher (up to an order of magnitude; see Fig. 6) during active phases.

An obvious question is why there should be such vigorous star formation in these regions. Star formation rates of $10-100 M_\odot$ yr$^{-1}$ kpc$^{-2}$ are orders of magnitude above those in normal galaxies and comparable to starburst galaxies. The answer may lie in the Schmidt law and the mass surface densities we have estimated in Table 3. Figure 7 shows these surface densities at the radii over which they were estimated, revealing a trend to higher densities on smaller scales and values of a few times $10^4 M_\odot$ pc$^{-2}$ in the central few tens of parsecs. The global Schmidt law, as formulated by Kennicutt (1998), states that the star formation rate depends on the gas surface density as $\Sigma_{\text{SF}} \propto \Sigma_{\text{gas}}^{1/4}$. If one assumes that 10%–30% of the mass in our AGN is gas, then this relation would predict time-averaged star formation rates in the
range 10–100 $M_\odot$ yr$^{-1}$ kpc$^{-2}$, as have been observed. That the high star formation rates may simply be a consequence of the high mass surface densities is explored further by E. K. S. Hicks et al. (2008, in preparation).

**Stellar luminosity.**—As a consequence of the high star formation rates, the stellar luminosity per unit area close around the AGN is very high in these objects. Despite this, because the star formation is occurring only in very small regions, the absolute luminosities are rather modest. This can be seen in Figure 8, which shows the bolometric luminosity of the stars as a fraction of the entire bolometric luminosity of the galaxy. We have calculated a range for the ratio $L_{\text{bol}}$/L$_K$ appropriate for each galaxy based on the ages in Table 3 for different $\tau_{\text{SF}}$. Because we assume that all the $K$-band stellar continuum is associated with the young stars, we have adopted the lower end of each range in an attempt to minimize possible overestimation of $L_{\text{bol}}$. The resulting values for the ratio used span 30–130, within a factor of 2 of the “baseline” value of 60 given in §3. In the central few tens of parsecs, young
stars contribute a few percent of the total. But integrated over size scales of a few hundred parsecs, this fraction can increase to more than 20%. On these scales, the star formation is energetically significant when compared to the AGN. Such high fractions imply that on the larger scales the extinction to the young stars must be relatively low. On the other hand, on the smallest scales where in absolute terms the stellar luminosity is small, there could in general be considerable extinction even at near-infrared wavelengths. In this paper we have not tried to account for extinction since it is very uncertain. The primary effect of doing so would simply be to increase the stellar luminosity above the values discussed here.

Figure 9 shows the stellar bolometric luminosity $L_{bol}$ integrated as a function of radius. All the curves follow approximately the same trend, with the luminosity per unit area increasing toward smaller scales and approaching $10^{13} L_\odot$ kpc$^{-2}$ in the central few parsecs. This appears to be a robust trend and will not change significantly even with large uncertainties of a factor of a few. It is remarkable that the luminosity density of $10^{13} L_\odot$ kpc$^{-2}$ is that estimated by Thompson et al. (2005) for ULIRGs, which they modeled as optically thick starburst disks. The main difference between the ULIRG model and the starbursts close around AGNs is the spatial scales on which the starburst occurs.

Based on this model, they argued that ULIRGs are radiating at the Eddington limit for a starburst, defined as when the radiation pressure on the gas and dust begins to dominate over self-gravity. The limiting luminosity-to-mass ratio was estimated to be $\sim 500 L_\odot M_\odot^{-1}$ by Scoville (2003). He argued that in a star cluster, once the upper end of the main sequence was populated, the radiation pressure would halt further accretion onto the star cluster and hence terminate the star formation. Following Thompson et al. (2005), we apply this definition to the entire disk rather than a single star cluster. For $10^{13} L_\odot$ kpc$^{-2}$, this implies a mass surface density of $2 \times 10^4 M_\odot$ pc$^{-2}$. Comparing these quantities to the AGNs we have observed, we find that on scales of a few tens
of parsecs they are an order of magnitude below the Eddington limit. On the other hand, we have already seen that the low $W_{\text{Br}}$ indicates that there is little ongoing star formation and hence that the starbursts are short-lived. This is important because short-lived starbursts fade very quickly. As shown in Figure 6, for a decay timescale of $\tau_{\text{SF}} = 10$ Myr, $L_{\text{bol}}^*/C_{24}$ will have decreased from its peak value by more than an order of magnitude at an age of 100 Myr. Thus, it is plausible, and probably likely, that while the star formation was active, the stellar luminosity was an order of magnitude higher. In this case the starbursts would have been at, or close to, their Eddington limit at that time.

The luminosity-to-mass ratio of 500 $L_\odot/M_\odot$ associated with the Eddington limit is in fact one that all young starbursts would exceed if, beginning with nothing, gas was accreted at the same rate that it was converted into stars. That, however, is not a realistic situation. A more likely scenario, shown in Figure 10, is that the gas is already there in the disk. In this case, a starburst with a star-forming timescale of 100 Myr could never exceed 100 $L_\odot/M_\odot$. To reach 500 $L_\odot/M_\odot$, the gas would need to be converted into stars on a timescale $\leq 10$ Myr. This timescale is independent of how much gas there is. Thus, for a starburst to reach its Eddington limit, it must be very efficient, converting a significant fraction of its gas into stars on very short $\sim 10$ Myr timescales. This result is consistent with the prediction of the Schmidt law, which states that disks with a higher gas surface density will form stars more efficiently. The reason is that the star formation efficiency is simply $\text{SFE} = \Sigma_{\text{SFR}}/\Sigma_{\text{gas}} \propto \Sigma_{\text{gas}}^{-0.4}$. Thus, from arguments based solely on the Schmidt law and mass surface density, one reaches the same conclusion that the gas supply would be used rather quickly and the lifetime of the starburst would be relatively short.

Summarizing the results above, a plausible scenario could be as follows. The high gas density leads to a high star formation rate, producing a starburst that reaches its Eddington limit for a short time. Because the efficiency is high, the starburst can only be active for a short time and then begins to fade. Inevitably, one would expect that the starburst is then dormant until the gas supply is replenished by inflow. This picture appears to be borne out by the observations presented here.

### 5. STARBURST-AGN CONNECTION

In the previous sections we have presented and discussed evidence that in general there appears to have been moderately recent star formation on small spatial scales around all the AGNs we have observed. Figure 11 shows the first empirical indication of a deeper relationship between the star formation and the AGN. In this figure we show the luminosity of the AGN, both in absolute units of solar luminosity and also in relative units of its Eddington luminosity $L_{\text{Edd}}$. Against the age of the most recent known nuclear star-forming episode. Since the AGN luminosity is not well known, we have made the conservative assumption that it is equal to half the bolometric luminosity of the galaxy, as may be the case for NGC 1068 (Pier et al. 1994; but see also Bland-Hawthorne et al. 1997). To indicate the expected degree of uncertainty in this assertion, we have imposed error bars of a factor of 2 in either direction, equivalent to stating that the AGN luminosity in these specific objects is likely to be in the range 25%–100% of the total luminosity of the galaxy. The Eddington luminosity is calculated directly from the black hole mass, for which estimates exist for these galaxies from reverberation mapping, the $M_{\text{BH}}-\sigma^*$ relation, maser kinematics, etc. These are listed in Table 2. For the age of the star formation, we have plotted the time since the most recent known episode of star formation began, as given in Table 3. For galaxies where a range of ages is given, we have adopted these to indicate the uncertainty; the mean of these, roughly $\pm 30\%$, has been used to estimate the uncertainty in the age for the rest of the galaxies. We note that these error bars reflect uncertainties in characterizing the age of the star formation from the available diagnostics and also in the star formation timescale $\tau_{\text{SF}}$. However, there are still many implicit assumptions in this process, and we therefore caution that the actual errors in our estimation of the starburst ages may be larger than that shown.
Conceding this, we do not wish to overinterpret the figure. Keeping the uncertainties in mind, Figure 11 shows the remarkable result that AGNs that are radiating at lower efficiency (≤ 0.1L/L_{Edd}) are associated with younger (≤ 50–100 Myr) starbursts, while those that are more efficient (≥ 0.1L/L_{Edd}) have older (≥ 50–100 Myr) starbursts. If one were to add to this figure the Galactic center, which is known to have an extremely low luminosity (L/L_{Edd} < 10^{-5}; Ozernoy & Genzel 1996; Baganoff et al. 2003) and to have experienced a starburst 6 ± 2 Myr ago (Pau mand et al. 2006), it would be consistent with the categories above. The inference is that either there is a delay between the onset of starburst activity and the onset of AGN activity, or star formation is quenched once the black hole has become active.

In § 4 we argued that the starbursts are to some extent self-quenching: that very high star formation efficiencies are not sustainable over long periods. In addition, an intense starburst will provide significant heat input to the gas, which is perhaps partially responsible for the typically high gas velocity dispersions in these regions (E. K. S. Hicks et al. 2008, in preparation). This itself could help suppress further star formation. Heating by the AGN could also contribute to this process and has been proposed as the reason why the molecular torus is geometrically thick (Pier 1996; Krolik 1992; Krolik 2007). It is also used to modulate star forma tion (at least on global scales) in semianalytic models of galaxy evolution (Granato et al. 2004; Springel et al. 2005). While this is certainly plausible, it does not explain why the star formation in some galaxies with a lower luminosity AGN has already ceased, nor why none of the AGNs associated with younger starbursts are accreting efficiently.

Instead, we argue for the former case above, that efficient fueling of a black hole is associated with a starburst that is at least 50–100 Myr old. It may be because of such a delay between AGN and starburst activity that recent star formation is often hard to detect close to AGNs: the starburst has passed its most luminous (very young) age and is in decline while the AGN is in its most active phase (see Fig. 6). This does not necessarily imply that the a priori presence of a starburst is required before an AGN can accrete gas, although it seems inevitable that one will occur as gas accumulates in the nucleus. Nor does it imply that all starbursts will result in fueling a black hole; indeed, it is clear that there are many starbursts not associated with AGNs. As we argue below, the crucial aspect may be the stellar ejecta associated with the starburst, and in particular, not just the mass-loss rate, but the speed with which the mass is ejected.

Winds from OB stars.—In the Galactic center, Ozernoy & Genzel (1996) proposed that it is the recent starburst there that is limiting the luminosity of the black hole. In this scenario, mechanical winds from young stars, both the outflow and the angular momentum of the gas (which is a consequence of the angular momentum of the stars themselves), hinder further inflow. The authors argued that almost none of the gas flowing into the central parsec reached the black hole because of outflowing winds from IRS 16 and He i stars in that region. Detailed modeling of the Galactic center region as a two-phase medium was recently performed by Cuadra et al. (2006). They included both the fast young stellar winds with velocities of 700 km s^{-1} (Ozernoy et al. 1997) and the slower winds of ~200 km s^{-1} (Pau mand et al. 2001) and also took into account the orbital angular momentum of the stars (Pau mand et al. 2001; Genzel et al. 2003), which had a strong influence on reducing the accretion rate. They found that the average accretion rate onto the black hole was only ~3 × 10^{-6} M_{\odot} yr^{-1}, although an intermittent cold flow superimposed considerable variability onto this. In contrast, the hypothetical luminosity that Ozernoy & Genzel (1996) estimate Sgr A* would have if it could accrete all the inflowing gas is 5 × 10^{43} ergs s^{-1}, typical of Seyfert galaxies. In principle, this process could be operating in other galactic nuclei where there has been a starburst that extends to less than 1 pc from the central black hole. However, it cannot explain the timescale of the delay we have observed, which is an order of magnitude greater than the main-sequence lifetime of OB and Wolf-Rayet stars.

Winds from AGB stars.—Stars of a few (1–8 M_{\odot}) solar masses will evolve onto the AGB at the end of their main-sequence lifetimes. The timescale for stars at the upper end of this range to reach this phase is ~50 Myr, comparable to the delay apparent in Figure 9. Since AGB stars are known to have high mass-loss rates, of order 10^{-7} to 10^{-4} M_{\odot} yr^{-1} at velocities of 10–30 km s^{-1} (Winters et al. 2003), they may be prime candidates for explaining the delay between starburst and AGN activity. To quantify this, we consider how much of the mass in the wind could be accreted by the central supermassive black hole. The Bondi parameterization of the accretion rate onto a point particle for a uniform spherically symmetric geometry is given by (Bondi 1952)

\[ \dot{M} = \frac{2\pi G^2 M^2 \rho}{(V^2 + c_s^2)^{3/2}}, \]

where \( M \) is the mass of the point particle moving through a gas cloud, \( V \) is the velocity of the particle with respect to the cloud, \( \rho \) is the density of the cloud far from the point particle, and \( c_s \) is the sound speed. This approximation is still used to quantify accretion onto supermassive black holes in models of galaxy evolution (Springel et al. 2005), even though it may be significantly inaccurate for realistic (e.g., turbulent) media (Krumholz et al. 2006). Here it is sufficient to provide an indication of the role that stellar winds may play in accretion onto a central black hole. The density of the stellar wind at a distance \( R \) from the parent star is given by

\[ \rho_{\text{wind}} = \frac{M_{\text{wind}}}{4R^2V_{\text{wind}}}. \]

In our case, \( R \) is the distance from the star to the black hole. One would therefore expect that the accretion rate onto the black hole could be written as (see also Melia 1992)

\[ \dot{M}_{\text{BH}} \sim \frac{G^2 M_{\text{BH}}^2 M_{\text{wind}}}{(V_{\text{wind}}^2 + c_s^2)^{3/2} V_{\text{wind}} R^2}. \]

This equation shows that \( \dot{M}_{\text{BH}} \propto V_{\text{wind}}^{-3} \). We have implicitly assumed that \( V_{\text{wind}} \) is greater than the orbital velocity \( V_{\text{orb}} \) of the star from which it originates. This is not the case for AGB winds, and so one reaches the limiting case of \( M_{\text{BH}} \propto V_{\text{orb}} \), where for the galaxies we have observed \( V_{\text{orb}} \sim 50–100 \) km s^{-1}. This is still at least an order of magnitude less than the winds from OB and Wolf-Rayet stars. Thus, even though the mass-loss rates from individual OB and Wolf-Rayet stars are similar to those of AGB stars, the AGB winds will fuel a black hole much more efficiently. However, for slow stellar winds that originate close to a 10^7 M_{\odot} black hole, the equation breaks down because the conditions of uniformity and spherical symmetry are strongly violated. Indeed, the apparent accretion rate exceeds the outflow rate, implying that essentially the entire wind can be accreted. For AGB wind velocities of 10–30 km s^{-1}, the maximum radius at which
the entire wind from a star in Keplerian orbit around a $10^7 \, M_\odot$ black hole will not exceed the escape velocity from that orbit (i.e., $V_{\text{wind}} + V_{\text{orb}} < V_{\text{esc}}$) is around 10–70 pc. We adopt the middle of this range, 40 pc, as the characteristic radius within which it is likely that a significant fraction, and perhaps most, of the AGB winds are accreted onto the black hole. Figure 9 indicates that the stellar luminosity within this radius is $\sim 2 \times 10^9 \, L_\odot$. It is this luminosity that has been used to scale the STARS model (for $75_\text{yr} = 10$ Myr and an age of 100 Myr) in Figure 6, and so one can also simply read off the mass loss from the figure. The mass-loss rate for such winds peaks at about 0.1 $M_\odot$ yr$^{-1}$ and then tails off proportionally to the $K$-band luminosity, leading to a cumulative mass lost of $2 \times 10^7 \, M_\odot$ after 1 Gyr (although most of the loss actually occurs within half of this time span). This mass-loss rate is sufficient to power a Seyfert nucleus for a short time. A typical Seyfert with $M_{\text{BH}} \sim 10^7 \, M_\odot$ requires 0.02 $M_\odot$ yr$^{-1}$ to radiate at the Eddington limit. Even for the short bursts we have modeled, Figure 6 shows that this can be supplied by AGB winds for starburst ages in the range 50–200 Myr.

We note that, taking an AGB star luminosity of $10^4 \, L_\odot$ (which is at the high end of the likely average; Nikolaev & Weinberg 1997), we then find that there are $\sim 2 \times 10^7$ AGB stars close enough to the black hole to contribute to accretion. In order to provide at least 0.02 $M_\odot$ yr$^{-1}$, the typical mass-loss rate per star must exceed $10^{-7} \, M_\odot$ yr$^{-1}$, which is the lower limit of the range measured for Galactic AGB stars given above. Thus, the mass losses and rates estimated here appear to be plausible.

The low speed of these winds means that they will not create much turbulence. We quantify this by considering their total mechanical energy $\frac{1}{2} m v^2$ integrated over the same time span, which is $\sim 10^{45} \, J$. These two quantities, gas mass ejected and mechanical energy, are compared to those for supernovae below.

**Supernovae.**—Type II supernovae are the stellar outflows most able to create turbulence in the interstellar medium (ISM), since they typically eject masses of $\sim 5 \, M_\odot$ at velocities of $\sim 5000 \, km \, s^{-1}$ (Chevalier 1977). Each supernova therefore represents a considerable injection of mechanical momentum and energy into the local environment. A large number of compact supernova remnants are known, for example, in M82 and Arp 220, and are believed to have expanded into dense regions with $n_H \sim 10^{3}–10^{4} \, cm^{-3}$ (Chevalier & Fransson 2001). These authors argue that such remnants become radiative when they reach sizes of 1 pc, at which point the predicted expansion velocity will have slowed to $\sim 500 \, km \, s^{-1}$. By this time, the shock front will have driven across $\sim 1000 \, M_\odot$ of gas. When integrated over the age of the starburst, even for low supernova rates (e.g., the current rate within 30 pc of the nucleus of NGC 3227 is $\sim 0.01 \, yr^{-1}$; Davies et al. 2006), this represents a substantial mass of gas that has been affected by supernova remnants. The STARS model we have constructed in Figure 6 indicates that typically one could expect $\sim 10^8$ supernovae to occur as a result of one of the short-lived starbursts, and that most of these will occur around 10–50 Myr after the beginning of the starburst. For a decay timescale of the star formation rate that is longer than $75_\text{yr} = 10$ Myr, this time span will increase. Hence, supernovae may also play a role in causing the observed delay between starburst and AGN activity.

STARS calculates the mass loss and mass-loss rates using a very simple scheme, assuming that a star ejects all of its lost mass at the end of its life on a stellar track. Thus, it does not calculate the mass lost from supernovae explicitly, but rather the combined mass lost from OB winds and supernovae, which is much higher. We therefore adopt the $\sim 5 \, M_\odot$ per supernova given above, which yields a total ejected mass of $\sim 8 \times 10^6 \, M_\odot$. This is about 40% of that released by AGB winds. However, since this gas is ejected at high speed and $M_{\text{BH}} \propto V_{\text{wind}}^{-4}$, the efficiency with which it can be accreted onto the black hole is extremely low. This can also be seen in the total mechanical energy of $\sim 10^{50} \, J$, which is several orders of magnitude greater than for AGB winds. In fact, the total mechanical energy exceeds the binding energy of the nuclear region, which is of order $10^{49} \, J$ (assuming $10^5 \, M_\odot$ within 40 pc). As a result, it is highly likely that supernovae cause some fraction of the gas to be permanently expelled. Indeed, superwinds driven by starbursts are well known in many galaxies. This is not important as long as either sufficient gas remains to fuel the AGN or more is produced by stellar winds, which, as we have argued above, appears to be the case for AGB stars.

6. CONCLUSIONS

We have obtained near-infrared spectra of nine nearby AGNs using AO to achieve high spatial resolution (in several cases better than 10 pc). For seven of these, integral field spectroscopy with SINFONI allows us to reconstruct the full 2D distributions and kinematics of the stars and gas. Although the individual AGNs are very varied, we have analyzed them in a consistent fashion to derive the stellar $K$-band luminosity, the dynamical mass, and the equivalent width of the Br$\gamma$ line. We have combined these with radio continuum data from the literature, which have been used to estimate the supernova rate. We have used these diagnostics to constrain STARS evolutionary synthesis models and hence characterize the star formation timescales and ages of the starbursts close around AGNs. Our main conclusions can be summarized as follows:

1. The stellar light profiles show a bright nuclear component with a half-width at half-maximum of less than 50 pc. In a number of cases these nuclear components clearly stand out above an inward extrapolation of the profile measured on larger scales. In addition, there are two cases that show kinematical evidence for a distinct stellar component, indicating that the nuclear stellar populations most probably exist in thick nuclear disks. The mean mass surface densities of these disks exceed $10^4 \, M_\odot \, pc^{-2}$

2. There is abundant evidence for recent star formation in the last 10–300 Myr. But the starbursts are no longer active, implying that the star formation timescale is short, of order a few tens of millions of years. While the starbursts were active, the star formation rates would have been much higher than the current rates, reaching as high as $1000 \, M_\odot \, kpc^{-2}$ in the central few tens of parsecs (comparable to ULIRGs, but on smaller spatial scales). These starbursts would have been Eddington limited. Due to the very high star-forming efficiency, the starbursts would have also exhausted their fuel supply on a short timescale and hence have been short lived. It therefore seems likely that nuclear starbursts are episodic in nature.

3. There appears to be a delay of 50–100 Myr (and in some cases perhaps more) between the onset of star formation and the onset of AGN activity. We have interpreted this as indicating that the starburst has a significant impact on fueling the central black hole, and we have considered whether outflows from stars might be responsible. While supernovae and winds from OB stars eject a large mass of gas, the high velocity of this gas means that its accretion efficiency is extremely low. On the other hand, winds from AGB stars ultimately dominate the total mass ejected in a starburst, and the very slow velocities of these winds mean that they can be accreted onto the black hole very efficiently.
The authors thank all those who assisted in the observations, and also the referee for a thorough review of the paper. This work was started at the Kavli Institute for Theoretical Physics at Santa Barbara and as a result was supported in part by the National Science Foundation under grant PHY05-51164. R. D. acknowledges the interesting and useful discussions he had there with Eliot Quataert, Norm Murray, Julian Krolik, and Todd Thompson.

Facilities: Keck:II (NIRSPAO, NIRC2), VLT:Yepun (NACO, SINFONI)

APPENDIX

INDIVIDUAL OBJECTS

This appendix contains specific details on the individual objects. We summarize our published results from near-infrared AO spectroscopy of individual objects and present a brief analysis of the new data for several other objects. The aim of re-assessing the data for Mrk 231 that have already been published is to ensure that it is analyzed using STARS in a manner that is consistent with the new data. For NGC 7469, we make a significant update of the analysis using new data from integral field spectroscopy. In general, for objects with new data, we provide only the part of the analysis relevant to understanding star formation around the AGN. Our intention is that a complete analysis for each object will be presented in future publications.

Our analyses are restricted to the nuclear region. Since there is no strict universal definition of what comprises the “nuclear region,” we explicitly state in Table 3 the size of the region we study in each galaxy. The table also presents a summary of the primary diagnostics. The way in which these have been derived and their likely uncertainties have been discussed in some detail already in § 3. As such, the description of these methods is not repeated, and in this appendix we discuss only issues that require special attention.

A1. SUMMARY OF STAR-FORMING PROPERTIES OF GALAXIES ALREADY STUDIED

A1.1. Mrk 231

A detailed analysis of the star formation in the nucleus of Mrk 231 at a resolution of about 0.18″ (150 pc) was given in Davies et al. (2004b). Here we summarize only the main points; no new data are presented, but the analysis is updated using STARS to make it consistent with the other objects studied in this paper.

The presence of stellar absorption features across the nucleus demonstrates the existence of a significant population of stars. The radial distribution and kinematics indicate that they lie, like the gas (Downes & Solomon 1998), in a nearly face-on disk. Davies et al. (2004b) found that the dynamical mass imposed a strong constraint on the range of acceptable starburst models, yielding an upper limit to the age of the stars of around 120 Myr. Reassessing the mass-to-light ratio using STARS models suggests that for the increased mass required by a more face-on orientation (Downes & Solomon 1998), the models yield an upper limit to the age of the stars of around 250 Myr. The conclusion was that the starburst was less than 80 Myr old and was already decaying. On these scales, either a small change of only a few degrees to the inclination (i = 10°) or a relatively short star formation timescale (10 Myr) would reduce the limit to the ~100 Myr previously estimated. This is more consistent with the extremely high supernova rate.

The stellar luminosity, found from the dilution of the CO absorption (Davies et al. 2004b), indicates that stars within 1″ (800 pc) of the nucleus contribute 25%–40% of the bolometric luminosity of the galaxy. Similarly, within 200 pc, stars comprise 10%–15% of $L_{bol}$. The age, star formation rate, and size scale (disk scale length of 0.18″–0.2″) are all consistent with high-resolution radio continuum imaging (Carilli et al. 1998).

A1.2. Circinus

Star formation in the central 16 pc of Circinus was addressed by Mueller Sánchez et al. (2006). The diagnostics given in Table 3 are taken from this reference. We used the depth of the CO(2–0) band head to estimate the stellar luminosity, combined with the narrow Brγ flux (which we argued originated in star-forming regions rather than the AGN narrow-line region) and the radio continuum, to constrain starburst models. The conclusion was that the starburst was less than 80 Myr old and was already decaying. On these scales it contributes 1.4% of $L_{bol}$, or more if extinction is considered. A similar nuclear star formation intensity was estimated by Maiolino et al. (1998), who were also able to study Circinus on larger scales. They found that the luminosity of young stars within 200 pc of the AGN was of order $10^{10} L_\odot$, hence comparable to the AGN.

A1.3. NGC 3227

An analysis similar to that for Circinus was performed on NGC 3227 by Davies et al. (2006), and the diagnostics given in Table 3 are taken from this reference. In this case we were also able to make estimates of and correct for contributions of (1) the narrow-line region to Brγ because there were clear regions along the minor axis that had higher dispersion; (2) the AGN to the radio continuum, by estimating the maximum contribution from an unresolved source; and (3) the bulge stars to the stellar luminosity, by extrapolating the radial profile of the bulge to the inner regions. The STARS models yielded the result that in the nucleus, star formation began approximately 40 Myr ago and must have already ceased. At the resolution of 0.85″, the most compact component of stellar continuum had a measured FWHM of 0.17″, suggesting an intrinsic size scale of ~12 pc. Young stars within 30 pc of the AGN (i.e., more than just the most compact region) have a luminosity of $\sim 3 \times 10^9 L_\odot$, which is ~20% of the entire galaxy.

A2. STAR-FORMING PROPERTIES OF GALAXIES WITH NEW DATA

A2.1. NGC 7469

Star formation on large scales in NGC 7469 has been studied by Genzel et al. (1995). They found that within 800 pc of the nucleus, a region that includes the circumnuclear ring, the luminosity from young stars was $\sim 3 \times 10^{11} L_\odot$, about 70% of the galaxy’s bolometric
luminosity. This situation is similar to that in Mrk 231. On smaller scales, the nuclear star formation in NGC 7469 was directly resolved by Davies et al. (2004a) on a size scale of 0.15"–0.20" (50–65 pc) FWHM. An analysis of the long-slit data, similar to that for Mrk 231, was made, making use of stellar absorption features, kinematics, and starburst models. We estimated that the age of this region was no more than 60 Myr under the assumption that the fraction of stellar light in the $K$ band in the central 0.2" was 20%–30%. Our new integral field SINFONI observations of NGC 7469 at a spatial resolution of 0.15" (measured from both the broad Br$\gamma$ and the nonstellar continuum profiles; see § 2) are used here to make a more accurate estimate of the nuclear $K$-band luminosity. They enable us to provide a short update to the detailed analysis in Davies et al. (2004a).

The SINFONI data show that the equivalent width of the 2.3 $\mu$m CO(2–0) is $W_{\text{CO}(2-0)} = 1.8$ Å in a 0.8" aperture and 0.9 Å in a 0.2" aperture. The corresponding $K$-band magnitudes are $K = 10.4$ and 11.8, respectively. If one takes the intrinsic equivalent width of the 2.3 $\mu$m CO(2–0) band head to be 12 Å (see § 3), one arrives at a more modest value of 8% for the stellar fraction of $K$-band continuum in the 0.2" aperture. The stellar $K$-band luminosity in this region is then $6 \times 10^7 L_\odot$. Comparing this to the dynamical mass in Davies et al. (2004a) yields a mass-to-light ratio of $M/L_K \sim 0.6 M_\odot L_\odot^{-1}$. Previously, extrapolation from a 37 mas slit to a filled aperture had led to an underestimation of the total magnitude but an overestimation of the stellar contribution. Fortuitously, these uncertainties had compensated each other. The same analysis for the 0.8" aperture yields a $K$-band stellar luminosity of $3 \times 10^8 L_\odot$ and hence $M/L_K \sim 1.6 M_\odot L_\odot^{-1}$.

The $K$-band data cube yields estimates of the upper limit to $W_{\text{Br}\gamma}$ of 17 and 11 Å in 0.2" and 0.8" apertures, respectively. This has been corrected for dilution of the stellar continuum (as described in § 3) but not for a possible contribution to the narrow Br$\gamma$ from the AGN. Hence, the actual $W_{\text{Br}\gamma}$ corresponding to only the stellar line and continuum emission will be less than these values, indicating that the star formation is unlikely still to be ongoing.

We estimate the age of the star formation using the STARS models in Figure 4. Within the 0.2" aperture this gives 100 Myr, comparable to our original estimate. Such a young age is supported by radio continuum measurements. With a 0.2" beam, Colina et al. (2001) reported that the unresolved core flux in NGC 7469 was 12 mJy at 8.4 GHz. With much higher spatial resolution of 0.03", Sadler et al. (1995) reported an upper limit to the unresolved 8.4 GHz continuum of 7 mJy. We assume that the difference of 5 mJy is due to emission extended on scales of 10–60 pc, which is resolved out of one beam but not the other. As discussed in § 3, star formation is a likely candidate for such emission. In this case, we would estimate the supernova rate to be $\sim 0.1$ yr$^{-1}$ and the ratio $10^{10} \nu_{\text{SN}}/L_K \sim 3$. This is likely to be a lower limit since there was only an upper limit on the core radio flux density. For a ratio of this order, even allowing for some uncertainty, Figure 4 implies an age consistent with no more than 100 Myr.

Within the 0.8" aperture, which we adopt in Table 3, continuous star formation is inconsistent with $W_{\text{Br}\gamma}$. For a star formation timescale of $\tau_{\text{SF}} = 100$ Myr, the mass-to-light ratio implies an age of 190 Myr, just consistent with the measured value of $W_{\text{Br}\gamma} = 11$ Å. If some of the narrow Br$\gamma$ is associated with the AGN rather than star formation, then a shorter star formation timescale is required. For $\tau_{\text{SF}} = 10$ Myr, the ratio $M/L_K$ yields an age of 110 Myr.

A2.2. IRAS 05189−2524

Figure 12 shows the $H$-band spectrum integrated across two segments of the NACO slit, located on either side of the nucleus. It shows that even away from the nucleus, the depth of the stellar absorption features is only a few percent. We have therefore decomposed the data into the stellar and nonstellar parts using both the stellar absorption features and the spectral slope of the continuum. The latter method has been shown to work for well-sampled data by Davies et al. (2004a). The rationale is that the hot dust associated with the AGN will be much redder than the stellar continuum. An AGN component is also expected to be unresolved for a galaxy at the distance (170 Mpc) of IRAS 05189−2524. The spectral slope was determined by fitting a linear function to the spectrum at each spatial position along the slit. It is plotted as a function of position in Figure 13, showing a single narrow peak. A Gaussian fit to this yields a spatial resolution of 0.12" (100 pc) FWHM. The stellar continuum, also shown in Figure 13, has been determined by summing the four most prominent absorption features: CO(4–1), Si I, CO(5–2), and CO(6–3). While a Gaussian is not an optimal fit to this profile, it does yield an approximate size scale, which we find to be 0.27" FWHM.

Quadrature correction with the spatial resolution yields an intrinsic size of 0.25". 

![Figure 12](https://example.com/figure12.png)
As a cross-check, in the figure we have compared the sum of these two components to the full continuum profile. The good match indicates that the decomposition appears to be reasonable.

Remarkably, the 200 pc size of the nuclear stellar light is very similar to that of the 8.44 GHz radio continuum map of Condon et al. (1991). With a beam size of 0.50" × 0.25", they resolved the nuclear component to have an intrinsic size of 0.20" × 0.17". In contrast to radio sources that are powered by AGNs and have brightness temperatures $T_B \gg 10^8$ K, the emission here is resolved and has a low brightness temperature of $\sim$4000 K. This implies a star-forming origin. Using their scaling relations further suggests that the flux density corresponds to a supernova rate of $\sim$1 yr$^{-1}$

As described in § 3, we have estimated the stellar luminosity by comparing the $H$-band spectrum to a template star to correct for dilution. We used HR 8465, a K1.5 I star for which the equivalent width of CO(6–3) is 4.2 Å, within the 4–5 Å range predicted by STARS in Figure 2. By extrapolating from the spatial profiles along the slit, we have estimated the integrated equivalent width within a 1.1" aperture, for which Scoville et al. (2000) gave an $H$-band magnitude of 11.83. Using all four features above, we find for the template $W = 14.4$ Å and for IRAS 05189–2524 $W_{\text{CO}(6–3)} = 6.7$ Å. This implies that in the central 1.1", approximately 45% of the $H$-band continuum originates in stars. Using the color conversion $H - K = 0.15$ from Figure 3 (see § 3), we find a $K$-band magnitude for the stars of 12.55 mag and hence a $K$-band stellar luminosity of $2 \times 10^9 L_{\odot}$. Putting these results together, we derive a ratio of supernova rate to $K$-band stellar luminosity of $\nu_{\text{SN}}(\text{yr}^{-1})/L_K(10^{10} L_{\odot}) \sim 5$. Applying corrections for extinction and an AGN contribution would tend to decrease this ratio.

As a second diagnostic, we use $W_{\text{Br}}$. We estimate the dilution of the $K$-band continuum via two methods. First, we measure $W_{Na_1} = 0.3$ Å, indicating a stellar fraction of 0.10–0.15. A consistency check is provided by the $H$-band dilution, which we extrapolate to the $K$ band using blackbody functions for the stars and dust assuming characteristic temperatures of 5000 and 1000 K, respectively. This method suggests that the $K$-band stellar fraction is around $\sim$0.14. Hence, correcting the directly measured equivalent width of the narrow Br$^\gamma$ for the nonstellar continuum yields $W_{\text{Br}} = 4-5$ Å.

Since IRAS 05189–2524 is close to face-on (Scoville et al. 2000), it is not straightforward to make a reliable estimate of the dynamical mass. Nevertheless, requiring $\nu_{\text{SN}}/L_K$ to be high while $W_{\text{Br}}$ is low already puts significant constraints on the star formation history. Thus, although the star formation has probably ended, the age is unlikely to be greater than 100 Myr and could be as low as 50 Myr where $\nu_{\text{SN}}/L_K$ peaks. For such ages the ratio $L_{\text{bol}}/L_K$ is in the range 100–150. Hence, for the young stars within 0.55" (450 pc) of the nucleus we find $L_{\text{bol}} \sim (2-3) \times 10^{11} L_{\odot}$, about 20% of $L_{\text{bol}}$ for the galaxy.

A2.3. NGC 2992

The spatial resolution of the $K$-band data for NGC 2992 has been estimated from both the broad Br$^\gamma$ and the nonstellar continuum (see § 2 and 3). The two methods yield symmetric PSFs, with FWHMs of 0.32" and 0.29", respectively, corresponding to 50 pc. The CO(2–0) equivalent width of $\sim$3 Å implies a stellar fraction of $\sim$0.25 within a radius of 0.4", and hence a stellar luminosity of $L_K = 3.5 \times 10^7 L_{\odot}$.

Unlike IRAS 05189–2524, the radio continuum in NGC 2992 is quite complex. Much of the extended emission on scales of a few arcseconds appears to originate from a superbubble, driven either by the AGN or by a nuclear starburst. On the other hand, most of the nuclear emission seems to be unresolved. With a beam size of 0.34" × 0.49", Wehle & Morris (1988) measured the unresolved flux to be 7 mJy at 5 GHz. At a resolution better than 0.1", Sadler et al. (1995) reported a 2.3 GHz flux of 6 mJy. Based on this, as well as nondetections at 1.7 and 8.4 GHz, they estimated the core flux at 5 GHz to be $<6$ mJy. Taking a flat spectral index, as indicated by archival data (Chapman et al. 2000), one might expect the 5 GHz core flux to be not much less than 6 mJy, leaving room for only $\sim1$ mJy in extended emission in the central 0.5". If we assume that this difference can be attributed to star formation, it implies a supernova rate of $\sim0.003$ yr$^{-1}$ and hence $10^{50} \nu_{\text{SN}}/L_K \sim 1$. Figure 4 shows that a ratio of this order is what one might expect for ages up to 200 Myr. However, given the uncertainty, it does not impose a significant constraint.

It is also difficult to quantify what fraction of the narrow Br$^\gamma$ is associated with star formation. This is made clear in Figure 14, which shows that the morphology of the line (second panel) does not follow that of the stars (left panel). In addition, particularly the southwest side is associated with velocities that are bluer than the surrounding emission, indicative of motion toward us. The western edge also
exhibits high velocity dispersion. Taken together, these suggest that we may be seeing outflow from the apex of an ionization cone with a relatively large opening angle. This interpretation would tend to support the hypothesis that the radio bubble has been driven by the AGN.

The stellar continuum appears to trace an inclined disk, the northwest side of which is more obscured (Fig. 14). However, the velocity dispersion is high, exceeding 150 km s\(^{-1}\) across the whole field (Fig. 15). This is similar to the 160 km s\(^{-1}\) reported by Nelson & Whittle (1995) from optical spectroscopy and suggests that we are seeing bulge stars. To analyze the radial luminosity profile, we have fitted it with both an \(r^{1/4}\) law and exponential profile. The fits in Figure 16 were optimized at radii \(r > 0.5''\) and then extrapolated inward, convolved with the PSF. Whether one could claim that there is excess continuum in the nucleus depends on the profile fitted. The \(r^{1/4}\) law provides a stronger constraint since it is more cuspy, and it suggests that there is no excess. Although this evidence is inconclusive, Figure 15 suggests that there is some kinematic evidence favoring the existence of a distinct nuclear stellar population. This comes in the form of a small unresolved drop in dispersion at the center, similar to those in NGC 1097 and NGC 1068. While the evidence in NGC 2992 is not compelling, the dispersion is consistent with there being an equivalent, but fainter, nuclear disk on a scale of less than our resolution of 50 pc. In general, it seems that the \(K\)-band light we are seeing is dominated by the bulge, and we are therefore unable to probe in detail the inner region where it seems that more recent star formation has probably occurred.

Thus, although the available data suggest that there has likely been recent star formation in the nucleus of NGC 2992, the only strong constraint we can apply is that continuous star formation in the central arcsecond over the last billion years can be ruled out since it would require \(W_{Br} > 10-15\) \AA. We therefore omit NGC 2992 from the discussion and analysis in §§4 and 5.

A2.4. NGC 1097

In NGC 1097, the first evidence for recent star formation near the nucleus was in the form of a reduction in the stellar velocity dispersion. Emsellem et al. (2001) proposed that this could be explained by the presence of a dynamically cold nuclear disk that had recently formed stars. Direct observations of a spiral structure in the central few arcseconds, from \(K\)-band imaging (Prieto et al. 2005)
and [N ii] streaming motions (Fathi et al. 2006), have since confirmed this idea. However, some issues remain open, such as why there are three spiral arms rather than the usual two, and why gas along one of them appears to be outflowing.

Our data, at a resolution of 0.25" measured from the $H$-band nonstellar continuum, also reveal the same spiral structure. Indeed, we find that it is traced by the morphology of the CO band head absorption, as well as by the 2.12 μm $C_2$ line. Interestingly, 1–0 $S(1)$ emission is stronger where the stellar features are weaker. This suggests that obscuration by gas and dust plays an important role. Figure 17 shows that an $r^{1/4}$ law, typical of stellar bulges, with effective radius $R_{e} = 0.5$" is a good fit to the stellar radial profile at $0.5'' < r < 1.8''$. It therefore seems reasonable to argue that at these radii it is only the gas that lies in a disk. In this picture the spiral structure in the stellar continuum arises solely due to extinction of the stars behind the disk. Extrapolating this fit, convolved with the PSF, to the nucleus indicates that at $r < 0.5''$ there is at least 25% excess continuum. There could be much more, given that it coincides with a change in the dominant kinematics.

For NGC 1097 we parameterized the kinematics of the gas and stars quantitatively using kinemetry. Based on the uniformity of the velocity field, we made the simplifying assumption that across the central 4" the gas lies in a single plane whose center is coincident with the peak of the nonstellar emission. We were then able to derive the position angle and inclination of the disk (see § 2). The 2D

Fig. 16.—Radial profile of the stellar continuum in NGC 2992 (1'' = 160 pc), derived from isophotal analysis. Filled circles denote the stellar continuum (i.e., already corrected for the nonstellar component). Overplotted with triangles are an $r^{1/4}$ law (top) and an exponential profile (bottom). The profiles were fitted at radii $r > 0.5''$ and extrapolated inward, convolved with the PSF, which is shown as open squares. Both fits are equally good at $r > 0.5''$, but only the exponential suggests that there might be excess continuum at the center, arising from a distinct stellar population. This is therefore inconclusive.

No. 2, 2007

STAR FORMATION IN AGNs

Fig. 17.—Radial profile of the stellar continuum in NGC 1097 (1'' = 80 pc). The filled circles denote the stellar continuum (i.e., already corrected for the nonstellar component). The triangles denote an $r^{1/4}$ profile fitted to radii $r > 0.5''$ and extrapolated inward. This model has been convolved with the PSF, shown as open squares for comparison. Note that even though an exponential profile might match the data equally well, an $r^{1/4}$ profile provides a stronger constraint on whether there is excess continuum at the center.
The kinematics of the stars is traced via the CO(2–0) absorption band head, and that of the gas through the 1–0 S(1) emission line. These independently yielded similar parameters: both gave a position angle of −49°, and their inclinations were 43° and 32°, respectively. These are fully consistent with values found by other authors (Storchi-Bergmann et al. 2003; Fathi et al. 2006). The resulting rotation curves and velocity dispersions are shown in Figure 18. The residuals, which can be seen in the velocity field of the gas but not the stars, and their relation to the spiral structure described above will be discussed elsewhere (R. I. Davies et al. 2008, in preparation).

The important result here is that at our spatial resolution, we find that the central stellar dispersion is $V_t = 100$ km s$^{-1}$, less than the surrounding 150 km s$^{-1}$ and also less than that in the seeing-limited spectra of Emsellem et al. (2001). In the same region we find that the rotation velocity of the gas starts to decrease rapidly, and its dispersion increases from $V_t = 40$ to ~80 km s$^{-1}$.

Figure 18 also shows that while the kinematics of the stars and gas is rather different at large (>0.5″) radii, it is remarkably similar at radii <0.5″. This certainly provides a strong indication that in the nuclear region the stars and gas are coupled, most likely in a (perhaps thick) disk, and that the stars in this disk, which are bright and hence presumably young, give rise to the excess stellar continuum observed. Evidence for a recent starburst has been found by Storchi-Bergmann et al. (2005) through optical and UV spectra. They argued that a number of features they observed could only arise from a $10^6 M_\odot$ instantaneous starburst, which occurred a few million years ago and is reddened by $A_V = 3$ mag of extinction. Using STARS, we have modeled this starburst as a $10^6 M_\odot$ burst beginning 8 Myr ago with an exponential decay timescale of 1 Myr. The age we have used is a little older to keep the Brγ equivalent width low, and at this age, the model predicts $W_{Br\gamma} = 4$ Å. As Figures 19 and 20 show, the observed Brγ is weak, although perhaps slightly resolved. Corrected for the nonstellar continuum, we measure only $W_{Br\gamma} \sim 1$ Å. However, the bulge population may account for a significant fraction of the K-band stellar continuum. Correcting also for this could increase $W_{Br\gamma}$ to 2–5 Å, consistent with that of the model, assuming that the Brγ is associated with the starburst rather than the AGN. To within a factor of a few, the scale of the model starburst is also consistent with that measured: In the central 0.5″ we measure a Brγ flux of $2 \times 10^{-19}$ W m$^{-2}$, compared to that predicted by the model of $5 \times 10^{-19}$ W m$^{-2}$. Given the uncertainties (factors of a few) both in the parameters of the starburst model and also in the corrections we have applied to the data, we consider this a good agreement.

We cannot constrain the starburst further due to its compactness. Storchi-Bergmann et al. (2005) found that it was occurring in the central 0.2″, whereas our resolution is only 0.25″. The Brγ emission is confined to the central 0.4″–0.5″, although its size is hard to
measure due to its weakness with respect to the stellar absorption features. In this region the K-band stellar luminosity is $4.5 \times 10^6 L_\odot$. To estimate the dynamical mass, we use the mean kinematics of the stars and gas, i.e., $V_{\text{rot}} = 40$ km s$^{-1}$ (corrected for inclination) and $\sigma = 90$ km s$^{-1}$ (this is the central value, which is least biased by bulge stars), yielding $1.4 \times 10^8 M_\odot$. This is actually dominated by the black hole, which has a mass of $(1.2 \pm 2) \times 10^6 M_\odot$ (Lewis & Eracleous 2006). The difference between these implies a mass of gas and stars of $\sim 2 \times 10^7 M_\odot$, although with a large uncertainty. The associated mass-to-light ratio is $M/L_K \sim 4$. On its own, this implies that over the relatively large area that it encompasses, the maximum characteristic age for the star formation is a few hundred million years. If one speculates that star formation has been occurring sporadically for this timescale, then the starburst seen by Storchi-Bergmann et al. (2005) is the most recent active episode.

In order to make a rough estimate of the supernova rate in the central region, we make use of measurements reported by Hummel et al. (1987). They find an unresolved component (size $< 0.1''$) with 5 GHz flux density $3.5 \pm 0.3$ mJy, but at lower resolution there is a $4.1 \pm 0.3$ mJy component of size $1''$. As discussed in § 3, we assume that the difference (albeit with only marginal significance) of $0.6 \pm 0.4$ mJy is due to star formation in the central region, which implies a supernova rate of $6 \times 10^{-4} \text{ yr}^{-1}$ and hence $10^{10} \text{yr}^{-1}/\text{SN}$, a value consistent with rather more recent star formation. Indeed, when compared to Figure 4, this and the low $W_{\text{Br}}$, imply a young age and short star formation timescale. For $t_{\text{SF}} = 10$ Myr the age is $60$–$70$ Myr; for an instantaneous burst of star formation, the age would be $\sim 10$ Myr, broadly consistent with that of Storchi-Bergmann et al. (2005).

Thus, although our data do not uniquely constrain the age of the starburst in the nucleus of NGC 1097, they do indicate that recent star formation has occurred, and they are consistent with a very young compact starburst similar to that derived from optical and UV data.

### A2.5. NGC 1068

Evidence for a stellar core in NGC 1068 with an intrinsic size scale of $\sim 45$ pc was first presented by Thatte et al. (1997). Based on kinematics measured in large ($2''$–$4''$) apertures, they assumed that the core was virialized and estimated a mass-to-light ratio based on this assumption leading to an upper limit on the stellar age of 1600 Myr. Making a reasonable correction for an assumed old component led to a younger age of 500 Myr.

Stellar kinematics from optical integral field spectra (Emsellem et al. 2006; Gerssen et al. 2006) shows evidence for a drop in the stellar velocity dispersion in the central few arcseconds to $\sigma_r \sim 100$ km s$^{-1}$, inside a region of higher 150–200 km s$^{-1}$ dispersion (presumably the bulge). Our near-infrared AO data are able to fully resolve the inner region where $\sigma_r$ drops, as shown in Figure 21. As for NGC 1097, the velocity distribution of the stars was derived through kinematics, again making use of the uniformity of the stellar velocity field to justify the simplifying assumption that the position angle and inclination do not change significantly in the central $4''$. The derived inclination of $40''$ and position angle of $85''$ are quantitatively similar to those found by other authors in the central few tens of arcseconds (Emsellem et al. 2006; Gerssen et al. 2006; García-Lorenzo et al. 1999). The uniformity of the stellar kinematics is in contrast to molecular gas kinematics, as traced via the $1-0$ $S(1)$ line, which is strongly perturbed and shows several distinct structures superimposed. These are too complex to permit a comparably simple analysis and will be discussed, together with the residuals in the stellar kinematics, in a future work (F. Mueller Sánchez et al. 2008, in preparation).

The crucial result relevant here is that at our $H$-band resolution of $0.1''$ we find that $\sigma_r$ reduces from $130$ km s$^{-1}$ at $1''$–$2''$ to only $70$ km s$^{-1}$ in the very center. That there is in the same region an excess in the stellar continuum is demonstrated in Figure 22. Here we show the radial profile of the stellar continuum from both SINFONI integral field spectra out to a radius of $2''$ and NACO long-slit spectra out to $5''$ (350 pc). At radii $1''$–$5''$, corresponding roughly to the region of high stellar dispersion measured by Emsellem et al. (2006), the profile is well matched by an $r^{1/4}$ law, as one might expect for a bulge. At radius $r < 1''$, the same radius at which we begin to see a discernible reduction in the stellar dispersion, the stellar continuum increases by as much as a factor of 2 above the inward extrapolation of the profile, indicating that there is extra emission. As for NGC 1097, the combined signature of dynamically cool kinematics and excess emission is strong evidence for a nuclear disk that has experienced recent star formation.
We can make an estimate of the characteristic age of the star formation in the central arcsecond based on the mass-to-light ratio in a similar way to Thatte et al. (1997). Because the stars appear to lie in a disk, we estimate the dynamical mass as described in §3 from the stellar kinematics, using the rotation velocity and applying a correction for the dispersion. The stellar rotation curve is essentially flat at $V_\text{c} = 45$ km s$^{-1}$ (corrected for inclination). We also take $\sigma_\text{c} = 70$ km s$^{-1}$, which is the central value and hence least biased by the high-dispersion bulge stars. These lead to a mass of $1.3 \times 10^8 M_\odot$ within $r = 0.5''$ (35 pc) and a mean surface density of $3 \times 10^4 M_\odot$/pc$^2$. Correcting for the nonstellar continuum, the $H$-band magnitude (which the behavior of $\sigma_\text{c}$ indicates is dominated by the disk emission) in the same region is 11.53 mag. For $H - K = 0.15$ mag (Fig. 4), we find $L_K = 4.3 \times 10^7 L_\odot$ and hence $M/L_K = 3 M_\odot L_\odot^{-1}$. If no star formation is ongoing, this implies a characteristic age of 200–300 Myr fairly independent of the timescale (for $t_{\text{SF}} \lesssim 100$ Myr, see Fig. 4) on which stars were formed. We note that this is significantly younger than the age estimated by Thatte et al. (1997) primarily because their mass was derived using a higher $\sigma_\text{c}$ corresponding to the bulge stars.

The assumption of no current star formation is clearly demonstrated by the Br$\gamma$ map in Figure 23. Away from the knots of Br$\gamma$, which are associated with the coronal lines and the jet rather than possible star formation, the equivalent width is $W_{\text{Br}\gamma} \sim 4$ Å. This is significantly less than that for continuous star formation of any age. Thus, while it seems likely that star formation has occurred in the last few hundred million years, it also seems an unavoidable conclusion that there is no current star formation.

To complete our set of diagnostics for NGC 1068, we consider also the radio continuum. This is clearly dominated by phenomena associated with the AGNs and jets, and our best estimate of the flux density away from these features is given by the lowest contour in maps such as Figure 1 of Gallimore et al. (2004). From this we estimate an upper limit to the 5 GHz continuum associated with star formation of 128 mJy within $r < 0.5''$, which also seems an unavoidable conclusion that there is no current star formation.

A2.6. NGC 3783

At near-infrared wavelengths, the AGN in NGC 3783 is remarkably bright. Integrated over the central 0.5'' less than 4% of the $K$-band continuum is stellar. In addition, the broad Brackett lines are very strong and dominate the $H$ band. Both of these phenomena...
are immediately clear from the $H$- and $K$-band spectra in Figure 24. However, it does mean that the spatial resolution can be measured easily from both the nonstellar continuum and the broad emission lines (see § 2). We find the $K$-band PSF to be symmetrical with an FWHM of $0.17''$.

Due to the ubiquitous Brackett emission in the $H$ band, we were unable to reliably trace the stellar absorption features and map out the stellar continuum. Instead, we have used the CO(2-0) band head at 2.3 μm even though the dilution at the nucleus itself is extreme. The azimuthally averaged radial profile is shown in Figure 25 together with the PSF for reference. At radii from 0.2'' to 1.6'' (the maximum we can measure) the profile is well fitted by an $r^{1/4}$ de Vaucouleurs law with $R_e = 0.6''$ (120 pc). As has been the case previously, at smaller radii we find an excess that here is perhaps marginally resolved. Thus, a substantial fraction of the near-infrared stellar continuum in the central region is likely to originate in a population of stars distinct from the bulge.

We were unable to measure the stellar kinematics due to the limited signal-to-noise ratio. Instead, we used the molecular gas kinematics to estimate the dynamical mass. As before, we used kinemetry to derive the position angle of $-14'$ and the inclination in the range $35' - 39'$. This orientation is consistent with the larger ($20''$) scale isophotes in the $J$-band 2MASS image and implies that in NGC 3783 there is no significant warp on scales of 50 pc–4 kpc. A small inclination is also consistent with its classification as a Seyfert 1. Adopting these values, the resulting rotation curve is shown in Figure 26. At very small radii the rising rotation curve may be the result of beam smearing across the nucleus. At $r > 0.2''$, the falling curve suggests that the rotation is dominated by the central ($r < 0.2''$) mass, perhaps the supermassive black hole. We estimate the dynamical mass within a radius of 0.3'' (60 pc), corresponding to the point where the excess continuum begins and also where the rotation curve appears to be unaffected by beam smearing.

Taking $V_{\text{rot}} = 60$ km s$^{-1}$ and $a = 35$ km s$^{-1}$, we derive a dynamical mass of $M_{\text{dyn}} = 1.0 \times 10^8 M_\odot$. The black hole mass of $3 \times 10^7 M_\odot$ (from reverberation mapping; Peterson et al. 2004) is only 30% of this and so cannot be dominating the dynamics on this scale unless its
mass is underestimated. With respect to this, we note that Peterson et al. (2004) claim that the statistical uncertainty in masses derived from reverberation mapping is about a factor of 3. Alternatively, there may be a compact mass of gas and stars at $r < 0.300$. However, including C27 in the mass estimate implicitly assumes that the dispersion arises from macroscopic motions. On the other hand, because we are observing only the hot H$_2$, it is possible that the dispersion is dominated by turbulence arising from shocks or UV heating of clouds that generate the 1–0 S(1) emission, issues that are discussed in more detail by E. K. S. Hicks et al. (2008, in preparation). In this case we will have overestimated the dynamical mass. Excluding C27 from the mass estimation yields $M_{\text{dyn}} = 5 \times 10^7 M_{\odot}$. We consider these two estimates as denoting the maximum range of possible masses. Subtracting $M_{\text{BH}}$ then gives a mass of stars and gas in the range $(2 \times 10^7) - (10^7) M_{\odot}$, implying a mass surface density of $1700 \pm 6000 M_{\odot}/pc^2$ and $M/L_K = 0.6 - 2.1 M_{\odot}/L_\odot$. Based on these ratios alone, Figure 4 indicates that the characteristic age of the star formation may be as low as $\approx 70$ Myr, although it could also be an order of magnitude greater. Without additional diagnostics we cannot discriminate further.

We are unable to use Br$\gamma$ as an additional constraint on the star formation history. Its morphology and velocity field are similar to that of [Si vi] and rather different from the 1–0 S(1). It shows an extension to the north that appears to be outflowing at $>50$ km s$^{-1}$ (Fig. 27), perhaps tracing an ionization cone. Since the Br$\gamma$ resembles the [Si vi], it is reasonable to conclude that it too is associated with the AGN rather than star formation. Thus, the equivalent width of Br$\gamma$ (with respect to the stellar continuum) of $W_{\text{Br}\gamma} = 30 \pm 8$ represents an upper limit to that associated with star formation.

The radio continuum in the nucleus of NGC 3783 has been measured with several beam sizes at 8.5 GHz. For a beam of $1.59'' \times 0.74''$, Morganti et al. (1999) found that it was unresolved with a flux density of $8.15 \pm 0.24$ mJy. With a smaller $0.25''$ beam, Schmitt et al. (2001) measured a total flux density of 8.0 mJy dominated by an unresolved component of $7.7 \pm 0.05$ mJy. At smaller scales still of $\approx 0.03''$ corresponding to 6 pc, Sadler et al. (1995) placed an upper limit on the 8.5 GHz flux density of 7 mJy. Taken together, these results imply that there is some modest 8.5 GHz radio continuum of $0.7 - 1$ mJy extended on scales of $0.3'' - 1''$. Based on this, we estimate a supernova rate as described in § 3 of $\approx 0.007$ yr$^{-1}$, and hence a ratio $10^{10}v_{\text{SN}}/L_K \approx 2$. Given that the unresolved radio continuum on the smallest
scales is an upper limit, the extended component may be stronger and hence the true $v_{SN}/L_K$ ratio may be greater than that estimated here. Figure 4 then puts a relatively strong limit of $\lesssim 50$ Myr on the maximum age of the star formation.

This age is fully consistent with that above associated with our lower mass estimate. The value of $W_{Br\gamma} < 30$ Å above does not impose additional constraints, although we note that if the Br$\gamma$ flux associated with star formation is only a small fraction of the total, then it would imply that the timescale over which the star formation was active is no longer than a few times $\lesssim 10$ Myr. Therefore, in the nucleus ($r < 0.3''$) of NGC 3783 we adopt 50–70 Myr as the age of the star formation and $M_{dyn} = 2 \times 10^7 M_\odot$ as the dynamical mass excluding the central supermassive black hole.

REFERENCES

Abuter, R., Schreiber, J., Eisenhauer, F., Ott, T., Horrobin, M., & Gillesen, S. 2006, NewA Rev., 50, 398
Anantharamai, K., Viallefond, F., Mohan, R., Goss, W., & Zhao, J. 2000, ApJ, 537, 613
Asari, N., Vega, L., Garcia-Rissmann, A., González Delgado, R., Storchi-Bergmann, T., & Cid Fernandes, R. 2007, in IAU Symp. 235, Galaxy Evolution across the Hubble Time, ed. F. Combes & J. Palous (Cambridge: Cambridge Univ. Press), 71
Baganoff, F., et al. 2003, ApJ, 591, 891
Balcells, M., Graham, A., Domínguez-Palmero, L., & Peletier, R. 2003, ApJ, 582, L79
Bender, R., Burstein, D., & Faber, S. 1992, ApJ, 399, 462
Bland-Hawthorne, J., Lumsden, S., Voit, G., Cecil, G., & Weisheit, J. 1997, Ap&SS, 248, 177
Bondi, H. 1952, MNRAS, 112, 195
Bonnet, H., et al. 2004, Messenger, 117, 17
Brand, K., et al. 2007, ApJ, 663, 204
Capetti, A., Axon, D., Machetti, F., Marconi, A., & Winge, C. 1999, ApJ, 516, 187
Carilli, C., Wrobel, J., & Ulvestad, J. 1998, AJ, 115, 928
Chapman, S., Morris, S., Alonso-Herrero, A., & Falcke, H. 2000, MNRAS, 314, 263
Chevalier, R. 1977, ARA&A, 15, 175
Chevalier, R., & Fransson, C. 2001, ApJ, 558, L27
Cid Fernandes, R., Gu, Q., Melnick, J., Terlevich, E., Terlevich, R., Kunth, D., Rodrigues Lacerda, R., & Joguet, B. 2004, MNRAS, 355, 273
Colina, L., Alberdi, A., Torrelles, J., Panagia, N., & Wilson, A. 2001, ApJ, 553, L19
Condon, J. 1992, ARA&A, 30, 575
Condon, J., Huang, Z.-P., Yin, Q., & Thuan, T. 1991, ApJ, 378, 65
Côô, P., et al. 2006, ApJS, 165, 57
Cuadra, J., Nayakshin, S., Springel, V., & Di Matteo, T. 2006, MNRAS, 366, 358
Dasyra, K., et al. 2006, ApJ, 651, 835
Davies, R. 2007a, MNRAS, 375, 1099
———. 2007b, preprint (astro-ph/0703044)
