AGNs and Starbursts: What Is the Real Connection?

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Abstract It is now widely believed that the growth of massive black holes is closely linked to the formation of galaxies, but there have been few concrete constraints on the actual physical processes responsible for this coupling. Investigating the connection between AGN and starburst activity may offer some empirical guidance on this problem. I summarize previous observational searches for young stars in active galaxies, concluding that there is now compelling evidence for a significant post-starburst population in many luminous AGNs, and that a direct, causal link may exist between star formation and black hole accretion. Quantifying the ongoing star formation rate in AGNs, however, is much more challenging because of the strong contamination by the active nucleus. I discuss recent work attempting to measure the star formation rate in luminous AGNs and quasars. The exceptionally low level of coeval star formation found in these otherwise gas-rich systems suggests that the star formation efficiency in the host galaxies is suppressed in the presence of strong AGN feedback.

Key words: galaxies: active — galaxies: nuclei — (galaxies:) quasars: general — galaxies: Seyfert

1 INTRODUCTION

As two of the most widely studied extragalactic phenomena, AGN and starburst activity have often been conjectured to share a “connection,” although precisely what the nature of the connection is or how it comes about is not always stated. Many galaxies exhibit concurrent signatures of both an AGN and a starburst, and much attention has been devoted to sorting out which of the two processes dominates the energetics in these hybrid systems. The best-known example of such systems are the ultraluminous infrared galaxies, whose energy source has been the subject of much intense debate since their initial discovery over two decades ago (e.g., Soifer et al. 1984; Sanders & Mirabel 1996; Genzel et al. 1998; Tacconi et al. 2002). Less extreme examples of intermixed AGN and starburst activity have been frequently reported in lower luminosity AGNs such as Seyfert galaxies (e.g., Boisson et al. 2000; González Delgado et al. 2001). Implicit in many of these studies, although often not always clearly articulated, is the assumption that somehow the two processes involved—black hole accretion and star formation—are causally linked. Why must this be so? Black holes are nearly ubiquitous, at least in massive galaxies (see reviews in Ho 2004a), as is AGN activity of varying levels of intensity (Ho 2004b). And provided that cold gas exists in galaxies, it has little choice but to form stars, especially in the presence of dynamical perturbations. When galaxies crash together, as is the case in most ultraluminous infrared sources (e.g., Sanders & Mirabel 1996), why should it be surprising that we would find both the AGN and the young stars to light up simultaneously? What other option is there, especially for galaxies selected from infrared or ultraviolet surveys? To be sure, physically motivated evolutionary scenarios linking starbursts and AGNs have been proposed (e.g., Sanders et al. 1988), but quantitatively testing them is...
much trickier. We must distinguish truly causal connections from merely phenomenological ones.

There are a variety of concrete paths in which starbursts and AGNs might be physically linked. The collapse of very massive stars, especially in the early Universe, may give rise to the first population of seed black holes. According to some recent theories, compact super star clusters, which form preferentially in starburst environments, may provide conditions particularly conducive to the production of intermediate-mass black holes. Once formed, black holes can be fed by stars, either directly through tidal capture or indirectly through gas shed via stellar mass loss. Likewise, the energy liberated by black hole accretion can either trigger star formation (e.g., by dynamically compressing gas clouds through radio jets) or suppress it (e.g., by blowing away all the gas through strong AGN feedback). More generally, the discovery of scaling relations between central black hole masses and the bulge properties of their host galaxies (Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000) has stimulated a plethora of ideas linking black hole growth with galaxy assembly.

If everyone agrees that the growth of black holes must be closely linked with galaxy formation (e.g., Silk & Rees 1998; Kauffmann & Haehnelt 2000; Begelman & Nath 2005), there is no consensus as to exactly how accretion and star formation are really coupled. Are they well synchronized, or does one process precede the other, and if so, what is the time lag? When the black hole is actively growing, does the feedback from the AGN actually facilitate or inhibit star formation in the host galaxy? These important issues are unlikely to be settled through theoretical speculations or numerical simulations alone. Some empirical guidance from observations would be highly desirable.

2 POST-STARBURSTS IN AGNS

The host galaxies of AGNs of moderate to high luminosity frequently show spectroscopic signatures of A-type stars indicative of an intermediate-age, post-starburst stellar population (see review by Heckman 2004). The evidence has been most thoroughly documented in Seyfert galaxies (e.g., Boisson et al. 2000; González Delgado et al. 2001; Q. S. Gu and M. Imanishi, this meeting), but post-starbursts have also been reported in bona fide quasars (Brotherton et al. 1999; Canalizo & Stockton 2001; Z. Shang, this meeting). By contrast, the central (10–100 pc) regions of weaker AGNs, such as low-luminosity Seyferts and LINERs, nearly always possess an old stellar population (Ho et al. 2003; Sarzi et al. 2005). Notwithstanding the extensive evidence for intermediate-age stars in Seyferts and quasars, how do we establish a truly causal connection between star formation and AGN activity? This crucial step was achieved by Kauffmann et al. (2003), whose analysis of a large sample of narrow-line (Type 2) AGNs selected from the Sloan Digital Sky Survey (SDSS) revealed not only the frequent presence of intermediate-age stars, but, most importantly, that the post-starburst fraction in these objects increases with increasing AGN luminosity. This, in my view, constitutes the most convincing evidence to date for a direct, statistically significant connection between AGN and star formation activity.

As encouraging as this is, we must realize that the SDSS results of Kauffmann et al. pertain only to the post-starburst phase, on timescales of $\sim 10^8 - 10^9$ yr. While the lifetime of AGNs is currently quite uncertain, Martini (2004) estimates it to lie in the range of $10^6$ to $10^8$ yr, precisely in the regime inaccessible by the current optical absorption-line diagnostics. In order to put meaningful constraints on the time sequence of black hole and galaxy growth, we must attempt to estimate the stellar population that is roughly coeval with the AGN, namely the ongoing star formation rate (SFR) as imprinted by massive, ionizing stars (ages $\leq 10^7$ yr).

3 ESTIMATING STAR FORMATION RATES IN AGNS

How can the current SFR in AGNs be estimated? While a variety of SFR estimators have been developed for normal (inactive) galaxies (e.g., Kennicutt 1998; Gilfanov et al. 2004), nearly all of them are problematic when applied to active galaxies because of the strong confusion with emission from the AGN itself. For example, neither the mid-ultraviolet continuum strength nor
the recently proposed indicator using hard X-ray luminosity (e.g., Gilfanov et al. 2004) can be used, since both are ubiquitous in AGNs. In detail the ultraviolet and X-ray continuum properties of AGNs do differ from those of starbursts, but most survey-quality data rarely have the luxury of discerning this level of subtlety. Most discussions in favor of one process versus the other boil down to crude luminosity arguments based on precedence from low-redshift observations. The strength of the radio synchrotron emission is often used as a star formation tracer, but it is rendered useless in AGNs, even radio-quiet ones, because AGNs are never totally radio-silent, and because we still lack a fully predictive theory to explain the origin of jets in accretion-powered sources. Some investigators resort to morphological arguments: AGNs should be compact, whereas starbursts should be extended. I do not find such qualitative criteria very persuasive. Clearly some AGNs do produce extended radio lobes, and many starbursts are highly centrally concentrated. The far-infrared (FIR) luminosity offers a highly effective, reddening-insensitive measure of the SFR in inactive galaxies, and it has even been used in this same capacity in quasars (e.g., Beelen et al. 2004; P. Cox and X. Y. Xia, this meeting). However, we must worry the extent to which we can truly separate AGN heating from stellar heating. The exact apportionment is model-sensitive, depending on the detailed geometrical distribution of the dust. It is often casually assumed that the cooler dust component traced by the FIR continuum must be heated by stars, but, as shown by Sanders et al. (1989), it can be equally modeled by AGN heating of a warped disk. Incidentally, the radio–FIR correlation offers little clarification in this matter, since radio-quiet AGNs, apparently fortuitously, exhibit radio/FIR ratios that are quite similar to those found in starburst galaxies (see discussion in Sanders et al. 1989). In terms of line emission, none of the standard hydrogen recombination lines (e.g., Hα) offer a viable solution, since these lines are extremely prominent in the AGN spectrum itself.

There is, however, one last recourse. Spectroscopic surveys of distant galaxies, particularly for redshifts between $z \approx 0.4$ to 1, routinely use [O II] $\lambda$3727, a prominent nebular emission line in H II regions, to estimate SFRs. Since its original introduction by Gallagher et al. (1989), the utility of [O II] as a SFR indicator has been scrutinized by numerous authors (e.g., Kennicutt 1998; Cardiel et al. 2003; Hopkins et al. 2003; Kewley et al. 2004). The [O II] line suffers from two main drawbacks, namely its sensitivity to dust extinction and metallicity effects. Hopkins et al. (2003) find, from comparing SFRs derived from [O II] versus SFRs derived from radio and FIR continuum, that while dust extinction is certainly non-negligible, on average [O II] only suffers from an extinction of $A_V \approx 1$ mag (corresponding to a factor of $4 \rightarrow 5$). The amount of dust extinction increases with increasing SFR, and the above estimate applies to SFRs $\sim < 100$ $M_\odot$ yr$^{-1}$. Kewley et al. (2004) have evaluated the influence of metallicity variations, but this effect is less serious than dust extinction: plausible metallicity uncertainties of a factor of 2, for example, result in SFR variations of only $\sim 50\%$.

Ho (2005) recently proposed that the [O II] line can be used as an equally effective SFR estimator in the host galaxies of AGNs. To mitigate confusion by [O II] emission from the narrow-line region, this method should not be applied to low-ionization AGNs (i.e. LINERs, which include many radio galaxies), but rather should be limited to high-ionization sources, whose intrinsic [O II] line is both observed and predicted to be weak. In practice, this requirement is not too restrictive, since virtually all relatively luminous AGNs, including classical Seyferts and quasars, fall in this category. (The ionization state of AGNs generally correlates with their luminosity.) And, of course, it is the actively accreting sources that matter most in terms of black hole growth. If high-ionization AGNs experience substantial levels of ongoing star formation, the integrated contribution from H II regions will boost the strength of the [O II] line (compared to, say, [O III] $\lambda$5007, which can be largely ascribed to the AGN itself). In any case, the observed [O II] strength, after applying reasonable corrections for extinction and metallicity, provides an absolute upper limit to the total ongoing SFR in the host galaxy.

4 RECENT RESULTS

Using the [O II] technique described above, Ho (2005) reached some surprising conclusions, which I will summarize here, regarding the ongoing level of star formation in quasars. First
and foremost, the [O II] line is always very weak. Although measurements of the [O II] line in individual quasars are not widely published, statistical averages of very large samples of objects, as captured in “composite spectra,” are readily available for nearly all of the extant major quasar surveys (LBQS, FIRST, 2dF+6dF, SDSS). Examination of these composite spectra reveals a common trend: [O II] is clearly detected, but it is very weak, generally having a strength equal to 10%–20% of that of [O III] λ5007. This relative intensity is entirely consistent with a pure AGN origin, leaving little additional room for a significant contribution from H II regions. As an illustrative example, the LBQS composite of Francis et al. (1991) gives an [O II] equivalent width of 1.9 Å. For an average quasar luminosity of \(<M_B> \approx -23.5\) mag, an average redshift of \(<z> \approx 1.3\), and a continuum spectrum \(f_\nu \propto \nu^{-0.32}\) (Francis et al. 1991), we find \(<L_{[O\ II]}> = 9.8 \times 10^{41}\) erg s\(^{-1}\).* To convert this line luminosity into a SFR, we use the calibration of Kewley et al. (2004), adopting three simple assumptions (see Ho 2005 for a more detailed justification): (1) that the amount of dust extinction in AGN host galaxies is comparable to that deduced for moderately actively star-forming galaxies (\(A_V \approx 1\) mag; e.g., Hopkins et al. 2003); (2) that the metallicity is twice solar (e.g., Storchi-Bergmann et al. 1998); and (3) that one-third of the observed [O II] strength comes from H II regions (the rest attributed to the AGN). These assumptions lead to \(<\text{SFR}> \approx 7\ M_\odot\ yr^{-1}\).

As this result relied on composite spectra, Ho also examined a more limited sample of 25 nearby Palomar-Green (PG) quasars that have available individual measurements of [O II] flux. In this case, the limits on the current level of star formation are even more stringent. On average the [O II] line strengths (or their upper limits) translate into a SFR of \(\sim 1\ M_\odot\ yr^{-1}\). To place

*The following cosmological parameters are adopted: \(H_0 = 72\) km s\(^{-1}\) Mpc\(^{-1}\), \(\Omega_m = 0.3\), and \(\Omega_\Lambda = 0.7\).
4 RECENT RESULTS

Figure 2 Line ratios of Type 1 AGNs (small dots) and Type 2 quasars (large triangle, from composite spectrum of Zakamska et al. 2003, with internal extinction correction applied) compared with photoionization models. The large cross marks the location of the average value of the upper limits in our sample, which are consistent with the detections. Diagnostic diagrams showing (a) $[\text{O \ II}]$ $\lambda$5007/$H\beta$ vs. $[\text{O \ II}]$ $\lambda$3727/$[\text{O \ III}]$ $\lambda$5007 and (b) $[\text{O \ I}]$ $\lambda$6300/$[\text{O \ II}]$ $\lambda$5007 vs. $[\text{O \ II}]$ $\lambda$3727/$[\text{O \ III}]$ $\lambda$5007. Two grids are shown, representing hydrogen densities $n = 10^2$ cm$^{-3}$ (solid line) and $n = 10^4$ cm$^{-3}$ (dashed line). Each grid shows models for an ionization parameter of $U = 10^{-2}$, $10^{-2.5}$, $10^{-3}$, and $10^{-3.5}$ (left to right) and spectral index for the ionizing continuum of $\alpha = -2.5$, $-2$, $-1.5$, and $-1$ (bottom to top). See Kim, Ho, & Im (2005) for details.

this result on a firmer statistical footing, Kim, Ho, & Im (2005) have performed a systematic analysis of the narrow emission-line spectra of a homogeneous, statistically complete sample of $\sim$3600 Type 1 AGNs, selected to have redshifts $< 0.3$ from the Third Data Release of SDSS. The $[\text{O \ II}]$ luminosities are quite modest (Fig. 1), ranging from $10^{40}$ to $10^{42}$ ergs s$^{-1}$, with an average of $\langle L_{[\text{O \ II}] \rangle} = 5.2 \times 10^{40}$ ergs s$^{-1}$. Importantly, the observed $[\text{O \ II}]$ line strength, when viewed in the context of the rest of the optical narrow-line spectrum, is again entirely consistent with a pure AGN origin. This is shown in Figure 2, where the observed line ratios are compared to a new set of photoionization models. The measured range of $[\text{O \ II}]$/[O III] ratios can be easily reproduced by assuming relatively standard parameters for the AGN narrow-line region. In other words, there is no need for any additional source of excitation, such as that coming from hot, young stars. Nevertheless, adopting, as before, the conservative assumption that one-third of the $[\text{O \ II}]$ strength comes from star formation, we arrive at a mildly startling conclusion: $\langle SFR \rangle \approx 0.5 \ M_\odot \ yr^{-1}$. To better appreciate the peculiarity of this result, it is instructive to recall that the integrated SFRs of local spiral galaxies, including the Milky Way, lie in the range of $\sim 1 - 3 \ M_\odot \ yr^{-1}$ (Solomon & Sage 1988; Scoville & Good 1989).

Could the SFRs, especially of the PG and SDSS AGNs, be exceptionally low because the host galaxies are early-type (e.g., S0 and E) systems? Dunlop et al. (2003) conclude that low-redshift quasars predominantly reside in massive, evolved, early-type galaxies. If all low-redshift quasars have early-type, gas-poor hosts, this would explain why their SFRs are so low. Unfortunately, the existing imaging data for the SDSS sample do not provide strong constraints on the detailed morphologies of the host galaxies. However, the situation is much better for the PG sample, a number of which have been imaged at high resolution with the Hubble Space
Figure 3  (a) The dependence of SFR on molecular gas content in galaxies; the right and top axes give the alternative representation in terms of infrared luminosity and CO luminosity, respectively. The PG quasars from Ho (2005) are plotted as filled circles, with their SFRs luminosities estimated from [O II] measurements; upper limits are denoted with arrows. Three galaxy samples are included for comparison: isolated and weakly interacting galaxies (pluses, with best-fitting line (Solomon & Sage 1988), luminous infrared galaxies (crosses), and ultraluminous infrared galaxies (asterisks). The large triangle marks the location of the Milky Way. (b) Same as (a), but with the total infrared luminosities actually observed in the PG quasars marked with semi-filled circles. See Ho (2005) for details.

Telescope (Bahcall et al. 1997; Barth et al. 2004; Veilleux et al. 2005). With few exceptions, the host galaxies of PG quasars generally tend to exhibit a fairly prominent disk component, often accompanied by visible spiral arms and tidal features. The host galaxies of PG quasars are not exclusively giant ellipticals, not by a long shot. At least from a morphological point of view, many of them resemble bulge-dominated disk galaxies, and, as such, their SFRs should be comparable to, or, naively, perhaps even greater than, those of inactive, normal spirals. This appears not to be the case.

Suppose the host galaxies, despite having a prominent disk component and spiral arms, somehow possess less gas than usual, as has been suggested for “anemic” spirals (e.g., Bothun & Sullivan 1980). Or perhaps most of the gas has been blown out of the galaxy as a result of very efficient AGN feedback, as suggested by some numerical simulations. This, too, appears not to be so. In a recent millimeter interferometric survey of a complete subsample of the nearest PG quasars, Scoville et al. (2003) find that the majority of them in fact contain significant amounts of CO emission. Most of the CO emission remains unresolved within a 4'' beam, implying that the gas is confined within the central ∼5 kpc of the galaxies. This result is noteworthy in that Scoville et al. deliberately avoided any infrared selection that might bias the sample toward unusually dusty objects. Assuming a standard (Galactic) CO-to-H$_2$ conversion factor, the implied molecular gas content ranges from ∼10$^9$ to 10$^{10}$ $M_\odot$. Again, for comparison, the Milky Way is characterized by $M_{H_2}$ ≈ 2 × 10$^9$ $M_\odot$. The CO survey of Evans et al. (2001) further corroborates the view that PG quasars tend to be gas-rich (although the infrared selection applied in this study complicates the interpretation), as does the nearly ubiquitous detection of large quantities of dust by Haas et al. (2003) using ISO.
Now we are faced with an even deeper dilemma: Why are the SFRs so low, in spite of there being plenty of gas? To emphasize this point, Figure 3a shows the SFR plotted versus the molecular gas mass. In this star formation “efficiency” diagram, regular galaxies follow a roughly defined locus delineated by the diagonal solid line; infrared-luminous galaxies lie somewhat offset above the line; and ultraluminous infrared galaxies lie even more displaced still, illustrating the well-known fact that the most extreme starbursts convert gas to stars at a much higher efficiency. Within this landscape, it is quite striking that the PG quasars studied by Ho (2005) fall significantly below the locus not only of starburst galaxies, but also that of normal galaxies.

The interpretation of the above results, of course, is not immune from criticism. A number of uncertainties, such as extinction, may affect the SFRs estimated from the [O II] emission line, and the applicability of the Galactic CO-to-H$_2$ conversion factor may be debated. These concerns have been discussed in Ho (2005), and will not be repeated here. Suffice it to say, reasonable assumptions have been adopted, but currently it is difficult to prove whether these assumptions are correct or not. If they turn out to be wrong (e.g., the star-forming regions in AGN host galaxies are pathologically much more extincted than inactive galaxies of similar type and gas-richness), then we would be faced with a new challenge of having to explain them. Taken at face value, the current evidence indicates that the presence of a luminous AGN suppresses the star formation efficiency within the host galaxy.

5 ORIGIN OF THE FAR-INFRARED EMISSION IN QUASARS

While most people now agree that the FIR continuum in AGNs arises from thermal dust emission, there is no universal consensus on the origin of the dust’s heating source (e.g., Haas et al. 2003). Since the FIR continuum traces relatively cool dust temperatures, it is often taken for granted that the dust must be heated by stars, and many investigators proceed to utilize the FIR luminosity to derive SFRs, neglecting any possible contribution from the AGN. Enormous SFRs have been inferred in some high-redshift quasars, especially when molecular gas has been detected (e.g., Beelen et al. 2004). But as mentioned in § 3, the cooler dust component traced by the FIR does not automatically dictate that stars dominate the energetics; an extended, warped disk illuminated by a central AGN can easily mimic this signature (e.g., Sanders et al. 1989).

The [O II]-derived SFRs discussed above provide a new, independent constraint on the origin of the FIR emission in quasars, and it serves as a warning that the mere existence of large quantities of molecular gas in infrared-luminous systems, in the presence of a luminous AGN, does not guarantee that stars form at a high rate. If we were to blindly attribute all of the infrared emission to stellar heating, the SFRs deduced for the PG sample would be at least an order of magnitude larger than those obtained from the [O II] line (Fig. 3b; see Table 1 in Ho 2005). Taking the [O II]-derived SFRs at face value, it appears that the bulk of the infrared emission in the (optically selected) PG quasars is powered by accretion energy rather than young stars.

6 TYPE 2 QUASARS, A DIFFERENT KIND OF BEAST?

By contrast to normal (Type 1) quasars, which have low SFRs, the level of star formation activity in Type 2 quasars appears to be significantly more elevated. This somewhat unexpected result is discussed by Kim, Ho, & Im (2005), who find, from inspection of the composite spectrum of SDSS Type 2 quasars published by Zakamska et al. (2003), that the [O II] line in Type 2 quasars is approximately an order of magnitude stronger (relative to [O III], for the same [O III] luminosity) than in Type 1 quasars. The inferred SFR is $\sim 20 \, M_\odot \, \text{yr}^{-1}$, equivalent to that of a modest local starburst. Apart from the obvious implication that Type 1 and Type 2 quasars are not intrinsically the same (modulo viewing angle), we might postulate that the source of obscuration in the Type 2 sources arises not from a standard compact torus, but perhaps instead from more patchy or extended dust associated with the more abundant star-forming regions in the host galaxy. Without too much of a stretch, we can further speculate that perhaps Type 2 quasars in fact are the precursors of Type 1 quasars.
7 AGN FEEDBACK

Our appraisal of the strength of the [O II] emission line in Type 1 AGNs, based either on statistical averages of large number of sources or measurements of individual sources, leads to the conclusion that the ongoing SFR in the host galaxies is very modest. The low SFRs stem not from a deficiency in gas, for abundant molecular gas has been detected, at least for a representative sample of nearby sources. Evidently gas can withstand the ravages of AGN feedback, presumably because the gas preferentially lies in a plane, which, under most circumstances, has a small cross-section with the intrinsically anisotropic feedback field (either radiation or jets) of the AGN. The real mystery is why the gas, despite being plentiful, fails to form stars when the AGN is simultaneously most active (when it is viewed as a full-blown, optically revealed Type 1 AGN or quasar). What could be responsible for the anomalously low star formation efficiencies? One can easily envisage a number of ways in which the hard radiation field of an AGN can have a profound impact on the thermal and ionization structure of a molecular cloud (e.g., Maloney 1999; Begelman 2004; Di Matteo et al. 2005), but precisely how this leads to suppression of star formation remains to be fully elucidated. Clearly, simple prescriptions for star formation, such as the Schmidt law, usually adopted in numerical simulations of galaxy formation need to be evaluated more judiciously. I hope that theorists would take up the challenge to investigate this problem.

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