Session 7

The high-redshift context

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Male students from Dunsink Observatory entertain female students from University College Dublin. From right: Cóilín Ó Maoiléidigh, Sinead McGlynn, Paul Ward, Suzanne Foley.

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Normal and Starburst Galaxies in Deep X-ray Surveys

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Abstract. This paper reviews the nature of normal and starburst galaxies in deep X-ray surveys, focusing on the observational issues. Normal and starburst galaxies may be divided from AGN via X-ray/optical flux ratios, optical spectroscopic identification, hardness ratio, and X-ray luminosity. Each of these is discussed, including the possible impact on derived X-ray-Star Formation Rate (X-ray/SFR) correlations. The measured differences in the normal galaxy X-ray Luminosity Functions (XLFs) by SED type at $z \approx 0.3$–1.0 are also described.

The redshift frontiers of deep X-ray surveys are discussed, including those for individually detected accreting binary systems (Ultraluminous X-ray Sources at $z \approx 0.1$–0.3) and that for the highest-redshift X-ray detection of star formation (stacking analyses of Lyman Break Galaxies to $z \approx 4$). The paper closes with a discussion of normal galaxy studies with future X-ray missions such as Constellation-X, XEUS, and Generation-X.

Keywords. galaxies: evolution, galaxies: formation, galaxies: luminosity function, galaxies: active , X-rays: binaries, X-rays: diffuse background, X-rays: galaxies, X-rays: general.

1. Introduction

Since the launch of the *Chandra* X-ray Observatory over six years ago, normal and starburst galaxies have been routinely detected in X-rays over the interval ($0.1 < z < 1.0$). Reaching these redshifts means that we probe the billion-year timescales that are relevant to the evolution of populations such as accreting binary systems (please also see the contribution of Pranab Ghosh in this same IAU 230 volume). At the time of this writing, quiescent (Milky Way-type) galaxies have been detected to $z \approx 0.3$ in the deepest *Chandra* surveys (look-back time $\approx$ 3.4 Gyr; $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_{\rm M} = 0.30$, $\Omega_\Lambda = 0.70$) (e.g. Hornschemeier *et al.* 2003, 2004). Vigorously star forming galaxies [current SFRs $>$10 $M_\odot$ yr^{-1}] have been detected individually in deep X-ray surveys to $z \approx 1$ (look-back times of $\approx$ 7.7 Gyr; e.g., Alexander *et al.* 2002). Beyond $z \approx 1$, our knowledge of X-ray emission from normal/star-forming galaxies is largely confined to statistical analyses (stacking the X-ray emission from individually undetected galaxies to achieve an average detection). At $z > 1$, such studies have concentrated on the vigorously star-forming Lyman Break galaxy population. Lyman Break galaxies have been detected in the X-ray band as far away as $z \approx 4$ (look-back time 11.9 Gyr; the Universe was 1.5 Gyr old; Lehmer *et al.* 2005). Thus for the first time we may study the *evolution* of X-ray emission from galaxies over a large fraction of the age of the Universe.

X-ray emission from galaxies may be broadly divided into two forms: gravitational potential energy release from accretion processes and thermal emission from hot gas. Accretion processes may be divided among three main systems: where a lower mass ($\lesssim$1 $M_\odot$), and correspondingly longer-lived ($>$1 Gyr), star accretes onto either a neutron star or black hole (low-mass X-ray binary; hereafter LMXB), where a higher mass

($\gtrsim 5\ M_\odot$) and thus shorter-lived ($<10^7$ yr) star accretes onto a neutron star or black hole (high-mass X-ray binary; hereafter HMXB), and finally where accretion occurs onto a nuclear supermassive (10^6–$10^8\ M_\odot$) black hole (active galactic nucleus; hereafter AGN). For the moment ignoring AGN, it is thus expected that in early-type galaxies, with older stellar populations, we will find that X-ray emission is dominated by LMXBs and hot ISM. In late-type galaxies, we expect a mix of emission from hot gas, LMXBs, and HMXBs with starburst galaxies having a great amount of both hot gas and HMXBs. The definition of a "normal galaxy", the subject of this paper, is a galaxy which does *not* have a luminous AGN present.

2. Normal Galaxies and the X-ray Background

The number counts of X-ray-detected galaxies are now well-measured over four orders of magnitude in X-ray flux (see Figure 1; Bauer *et al.* 2004). In the 0.5–2 keV band, where the cosmic X-ray background is nearly fully resolved (Worsley *et al.* 2004), galaxies are a minority population to the faintest X-ray limits currently achieved. Including X-ray emission from stacking analyses, normal and starburst galaxies make <5% of the cosmic 0.5–2 keV X-ray background (Hornschemeier *et al.* 2002; Persic & Rephaeli 2003). Normal and starburst galaxies might make a larger contribution to the 2–10 keV background if a sufficiently large population of relativistic electrons is present in star-forming galaxies (resulting in Compton upscattering). Persic & Rephaeli (2003) show that due due to the increased energy density of the Cosmic Microwave Background at higher redshifts [$\propto (1+z)^4$], galaxies might make up to 15% of the 2–10 keV background. To date, however, there has been no highly confident detection of this non-thermal component in the nearby Universe, so it remains unconstrained.

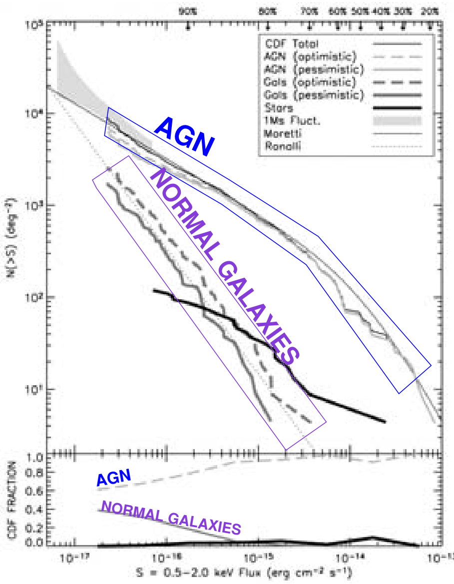

Figure 1. X-ray number counts in the 0.5–2.0 keV band, figure is adapted with permission from Bauer *et al.* (2004). The large blue and purple polygons mark the normal galaxy and AGN number counts. The galaxies rise sharply to faint X-ray fluxes whereas the AGN number counts are flattening. It one extrapolated the galaxy number counts, galaxies would dominate the number counts below $f_X \approx 5 \times 10^{-18}$ erg cm^{-2} s^{-1} (0.5–2 keV).

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3. Separating Normal Galaxies from AGN

There are several strategies for dividing normal galaxies from AGN, here we describe the use of X-ray/optical flux ratios, X-ray hardness ratios, and optical spectroscopy. We discuss the how galaxy classification affects how X-ray/SFR correlations are interpreted.

3.1. *X-ray/optical flux ratios*

With *ROSAT* it was discovered that most 0.5–2 keV point sources in deep surveys exist in a fairly narrow range of ratio of X-ray/optical flux ($-1 < \log \frac{f_X}{f_R} < +1$) and the overwhelming majority of these sources were found to be AGN. The first deep ($\gtrsim$200 ks) *Chandra* surveys found a significant number of X-ray sources at lower values of X-ray/optical flux ratio ($\lesssim 10^{-3}$; Hornschemeier *et al.* 2003). For reference, the Milky Way galaxy has X-ray/optical flux ratio $\approx 10^{-3}$.

How reliably can we use X-ray/optical flux ratio as a discriminator of AGN vs. normal galaxies? Typically, AGN and X-ray binary populations have unobscured X-ray spectra with photon indices of $\Gamma \approx 2$; the k-corrections for such a spectrum are small with redshift. Also, we become less sensitive to obscuring columns as we observe harder rest-frame emission, so the same population becomes relatively more X-ray bright with redshift. The net effect is that the X-ray/optical flux ratios of Seyfert 2 galaxies are expected to be lower at higher redshift due to this differential k-correction (Bauer *et al.* 2004; Ptak *et al.* 2006).

Peterson *et al.* (2006) took a sample of 23 nearby well-studied Seyfert 2 galaxies to determine the impact this k-correction could have on selection of galaxies and AGN at higher-z. These AGN were artificially placed at $z = 0.3$, the lowest redshift for which normal galaxy X-ray Luminosity Functions (XLFs) have been constructed (Norman *et al.* 2004). Many of these well-known Seyfert 2 galaxies would have ($-3 < \log \frac{f_X}{f_R} < -2$) at $z = 0.3$, clearly demonstrating that k-corrections are critically important in selecting galaxies by X-ray/optical flux ratio even at modest redshift.

Peterson *et al.* (2006) also examined the hardness ratios (hard-soft)/(hard+soft) counts of "pure Seyfert 2" galaxies (galaxies where the X-ray emission is clearly dominated by the AGN), finding that although AGN do cluster around harder band ratios, a significant tail towards soft X-ray colors is observed. The best strategy is thus to use redshifts to k-correct the X-ray/optical flux ratios and then use hardness ratio as a weak discriminator of AGN activity.

3.2. *Optical spectroscopy and the effect of classification on X-ray/SFR correlations*

Optical spectroscopy is essential for X-ray source identification as the typical number of detected X-ray counts in the deepest X-ray surveys is often <30 and X-ray-determined redshifts are not possible. However, there is often discordance between X-ray and optical classification. The most obvious case of this is the X-ray Bright, Optically Normal Galaxy population (XBONGs) so-called because their optical spectra are passive (red, absorption-dominated spectra with no emission lines) but they have very luminous hard X-ray emission (e.g., Comastri *et al.* 2002).

It is expected that at high-redshift the galaxy light might dilute the AGN and/or starburst features in spectra (Moran *et al.* 2002). The results of both Moran *et al.* (2002) and Peterson *et al.* ((2006)) indicate that obscured AGN can plausibly appear as "normal" galaxies at high redshift (however, please see Barger *et al.* 2003). Of course, some passive optical spectra simply indicate there is no luminous AGN present (e.g., the detection of hot gas in early-type galaxies; Hornschemeier *et al.* 2005).

How do we tell the difference? One strategy is to take the high signal-to-noise optical spectra of the Sloan Digital Sky Survey (Abazajian *et al.* 2005) and thus eliminate factors

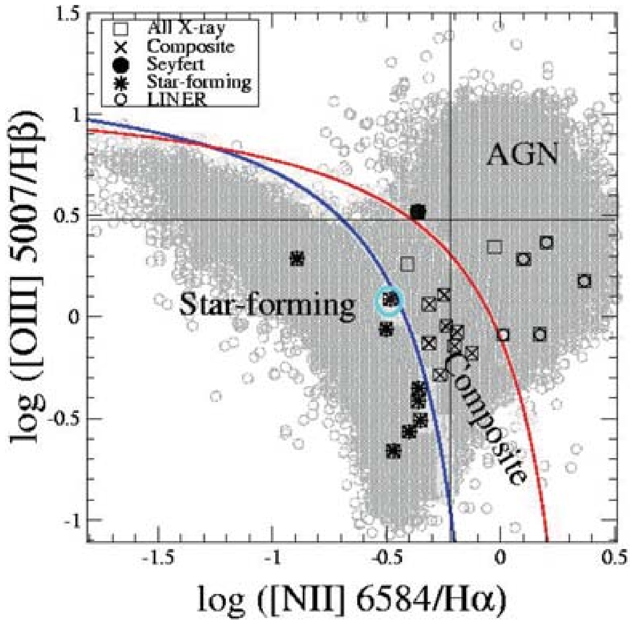

Figure 2. Emission-line ratio diagnostic diagram, adapted with permission from Hornschemeier *et al.* (2005). The grey in the background shows the SDSS DR3 galaxy sample and the black symbols are serendipitous *Chandra* detections. Theoretical modeling of starbursts has shown that even for extreme starburst galaxies should not exist above the red (upper curved) line in this diagram (Kewley *et al.* 2001). The blue (lower curved) line was proposed by Kauffmann *et al.* (2003) as the line below which AGN are not found. The cyan data point marks the location of a NLS1 galaxy, which was confirmed by its Balmer line widths exceeding its forbidden line widths.

such as optical dilution and/or inadequate coverage of key spectral features such as Hα. Hornschemeier *et al.* (2005) took this approach in an archival *Chandra* study of 42 serendipitously detected SDSS galaxies. Stellar population synthesis models were run for all of the galaxies (Tremonti *et al.* 2004) and the best-fit stellar continua subtracted. Galaxies were then divided into star-forming and AGN samples via emission-line ratio diagnostics ([OIII] 5007/Hβ versus [NII]/Hα; see Figure 2).

3.3. *X-ray/SFR Correlations for Carefully Classified Galaxies*

In galaxies with a higher ratio of SFR to stellar mass, where the LMXB component is expected to be negligible, the total X-ray luminosity may be dominated by HMXBs and thus serve as an SFR indicator (e.g., Grimm *et al.* 2003). We have taken several X-ray/SFR relations in the literature and converted them to the same bandpass and the same IMF (the IMF of Kroupa 2001) for conversions (see Figure 3). Among the serendipitously detected SDSS galaxies, the "pure" star-forming galaxies tend to clump around the lower X-ray/SFR correlations. These studies (Persic *et al.* 2004; Colbert *et al.* 2004) both removed contributions from hot gas and from evolved LMXB populations whereas the higher X-ray/SFR lines in Figure 4 are for *total* X-ray luminosity. Our results indicate that there is X-ray emission in many of those galaxies which is *not* associated with the HMXB population but likely is due to hot gas and/or the evolved component.

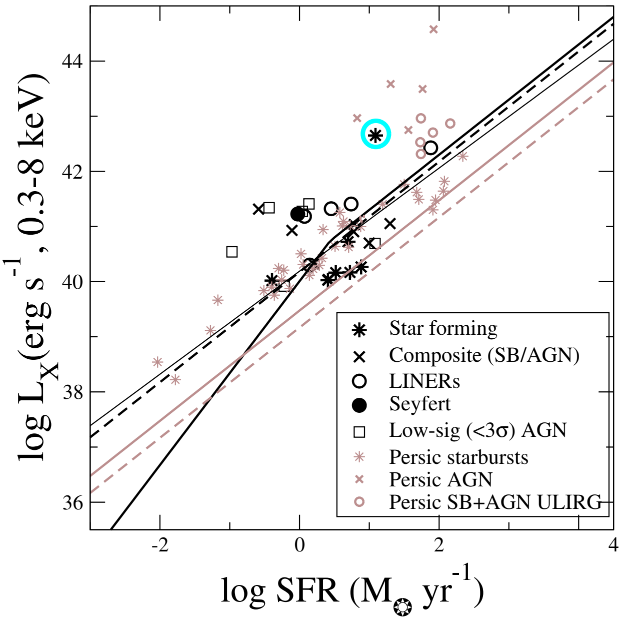

Figure 3. Total *Chandra* full-band X-ray luminosity of SDSS sources versus star-formation rate (SFR; Hornschemeier *et al.* 2005). The lines show the correlations from the literature, adjusted to the 0.3–8 keV band and a Kroupa IMF. The thin black, thick black, dashed black, pink solid and pink dashed lines are Bauer *et al.* (2002), Grimm *et al.* (2003), Ranalli *et al.* (2003), Persic *et al.* (2004), and Colbert *et al.* (2004) respectively. We also show the data on nearby galaxies from Persic *et al.* (2004).

4. X-ray Luminosity Functions

Revisiting the number counts of Figure 1, notice that there are *two lines* for both the AGN and galaxy number counts. These correspond to "optimistic" and "pessimistic" galaxy classification (Bauer *et al.* 2004) using observational properties such as X-ray luminosity, hardness ratio, and spectroscopic identification. Some of the first attempts to do such systematic galaxy classification include e.g., the Bayesian analysis of Norman *et al.* (2004). This work has allowed the first normal/starburst galaxy X-ray luminosity function to be constructed at $z \approx 0.3$ and $z \approx 0.7$ (Norman *et al.* 2004). There is clear (and expected) evolution in this XLF, which has a lognormal shape, similar to FIR luminosity functions (Takeuchi *et al.* 2004). Norman *et al.* (2004) interpret the lognormal shape as evidence of the multiplicative processes involved in accreting binary evolution.

Recently this work has been expanded using k-corrected X-ray/optical and X-ray/infrared flux ratios (resulting in less AGN contamination) and a larger multiwavelength dataset offered by the Great Observatories Origins Deep Survey (GOODS; Ptak *et al.* 2006). For the first time, we have been able to observe differences in galaxy X-ray luminosity functions by galaxy type (early and late-type SED; Georgantopoulos *et al.* 2005; Ptak *et al.* 2006, see Figure 4). The late-type SED XLF is found to track the FIR luminosity function better, indicating that it is tracing star formation.

5. Redshift Frontiers

5.1. *ULX Sources at $z > 0.1$*

An interesting frontier in the study of individual accreting binaries has been opened up by the discovery of off-nuclear X-ray emission in several dozen deep *Chandra* survey

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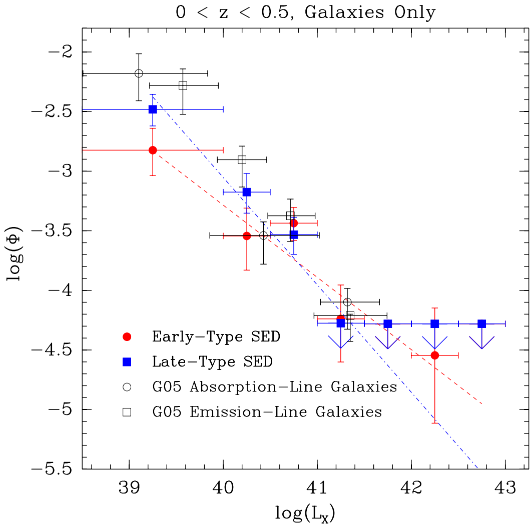

Figure 4. The $z \approx 0.3$ normal galaxy XLFs from Ptak *et al.* (2006) and Georgantopoulos *et al.* (2005). This figure was adapted with permission from Ptak *et al.* (2006). Clear difference in the early-type and late-type galaxy SED can be seen.

sources (Hornschemeier *et al.* 2004, B. Lehmer *et al.* 2006, in preparation). These sources, like the Ultraluminous X-ray sources observed in the local Universe, have full-band X-ray luminosities $\gtrsim 10^{39}$ erg s^{-1}, in excess of that expected for spherically symmetric Eddington-limited accretion onto "stellar" mass (5–20 $M_\odot$) black holes. These sources may still be consistent with stellar mass black holes, possibly representing an unstable, beamed phase in normal high-mass X-ray binary (HMXB) evolution (e.g. King *et al.* 2001) or might also represent a class of intermediate mass black holes ($\approx$ 500–1000 $M_\odot$, e.g., Colbert *et al.* 2002).

$\approx$20% of giant galaxies in the *Chandra* deep survey fields harbor these off-nuclear ULX sources (Hornschemeier *et al.* 2004), some of which show clear short-term variability. The ULX fraction measured here is only a lower limit; even *Chandra*'s sub-arcsecond spatial resolution often cannot resolve sources within the central $\approx$1–2 kpc of the nucleus and offsets of $\sim$1 kpc have been found for ULX sources in the local Universe (Colbert & Ptak 2002).

The binary LFs of galaxies predict few ULX sources per galaxy, so constructing samples such as these at $z \approx 0.1$ allow a statistical probe of the bright end of the binary LF. The initial results with 12 ULX sources found that the numbers/brightnesses of ULXs at $z \approx 0.1$ are consistent with a bright-end LF slope of $\alpha \approx 0.4$, characteristic of, e.g., the Antennae (Zezas *et al.* 2002).

5.2. *Lyman Break Galaxies*

Our current knowledge of the high-z star-forming Universe is dominated by studies in the rest-frame ultraviolet band (the observed-frame optical). The best-studied examples of high-z star-forming galaxies are the "Lyman Break" galaxies (Steidel *et al.* 1996; Shapley *et al.* 2003). These galaxies are of great cosmological importance, as they are vigorously forming stars (30–50 $M_\odot$ yr^{-1}) and exhibit rest-frame ultraviolet spectroscopic signatures of outflows (Shapley *et al.* 2003). It appears that such starburst outflows are required to correctly predict the low-mass end of the galaxy luminosity function (analogous to the AGN outflows affecting the high-mass end, e.g., Croton *et al.* 2006).

There are relatively few measures of SF that can reliably reach $z > 2$ (however see Hogg 2002). The lack of powerful wide-field NIR spectrographs make Hα studies beyond $z \approx 1$ very difficult. The depth of the currently deepest radio surveys is insufficient to detect moderately star-forming galaxies at $z > 1$. NUV emission lines (such as [OII]) are highly susceptible to uncertainties in metallicity (but see Kewley *et al.* 2004). Spitzer is certainly opening up the MIR/FIR band at high-z, but the large PSF ($>5''$ at $\lambda_{\rm obs} > 24\ \mu$m) makes confusion a problem at $z > 2$ in the most useful FIR bands.

The deepest *Chandra* surveys are not sensitive enough to individually detect Lyman Break galaxies. However, the sensitivity may be extended via stacking the X-ray emission from undetected sources. Despite the uncertainties in terms of why the X-ray/SFR correlation works even when non-HMXB components are included (see §3.3 and Hornschemeier *et al.* 2005), the reliability of X-ray emission as a possible SFR indicator has allowed numerous groups to study the average X-ray emission from star-forming galaxies. These analyses have verified ultraviolet dust-obscuration corrections (Seibert *et al.* 2002) and have probed star formation up to $z \approx 4$ (Lehmer *et al.* 2005). Although stacking X-ray emission from Lyman Breaks has become an industry (Brandt *et al.* 2001; Nandra *et al.* 2002; Reddy & Steidel 2004), the X-ray/SFR correlations have not been characterized well at the higher SFRs typical of Lyman Break galaxies (10–100 $M_\odot$ yr^{-1}). Individual detections of complete samples in this range of SFR, particularly in a UV-selected sample, would be very advantageous. We can look forward to new, lower-redshift "Lyman Break galaxy" samples from the GALEX mission (Heckman *et al.* 2005) for calibrating of the X-ray/SFR relation in the relevant high SFR range.

6. Summary and Considerations for the Future

X-ray studies of normal galaxies at high redshift have reached new levels of sophistication as we understand the biases in dividing them from AGN via observational properties such as X-ray/optical flux ratio, X-ray hardness, and optical spectroscopic type. The first galaxy XLFs have been measured, and constraints can be placed on the binary LF using ULX sources at high-z. Many of the uncertainties will be erased by the next generation X-ray mission, Constellation-X (constellation.gsfc.nasa.gov, will launch in 2015–2018), whose spectroscopic capabilities will allow us to use X-ray emission and absorption features to construct *X-ray* diagnostic diagrams. Constellation-X will have 1.5 m^2 collecting area at 1.25 keV; high spectral-resolution X-ray spectra for populations such as the Chandra-SDSS sample will easily be obtained in ~ 40 ks observations.

Chandra may go deeper, and the X-ray number counts indicate that at $f_X < 5 \times 10^{-18}$ erg cm^{-2} s^{-1}, we expect galaxies to become the most numerous X-ray emitting population. Missions such as XEUS (launching around 2018) and Generation-X (launching after 2025), with extremely large collecting areas (10 m^2 and 100 m^2, respectively), should detect and characterize galaxies up to $z \approx 5$, allowing us to measure starburst winds, etc. in galaxies as they are first forming.

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Discussion

KIM: Can you comment on the different classification schemes between Norman *et al.* & Bauer *et al*?

HORNSCHEMEIER: The Norman *et al.* classification was much more "optimistic" or open. It likely admitted too many low luminosity AGN, mainly due to weak constraints on hardness ratios and X-ray/optical flux ratios. The follow-on paper by Ptak *et al.* includes much more rigorously defined selection methods, including K-corrected X-ray/NIR flux ratios derived from K-band data. This selection admits fewer galaxies to the XLF sample.

MACCARONE: Will radio emission, especially from deep wide-field VLBI measurements, help with the separation of normal galaxies from AGN?

HORNSCHEMEIER: Yes, although we have the problem that current radio measurements aren't deep enough to compare with our deepest X-ray fields. We're hoping e-VLA, for example, will help a lot.

ELVIS: On the AGN-Starburst diagnostic plot you showed the Kewley line gives the maximum Starburst contribution and the Kauffmann line gives the minimum, so between these lines a galaxy could be either pure starburst, pure AGN or a mixture. Calling these objects 'Composite' may then be misleading.

HORNSCHEMEIER: The term "Composite" is admittedly ambiguous. These galaxies, however, are a mix of galaxies which are still actively star-forming and possess actively accreting SMBH. That is, both processes are going on in all these galaxies. Tim Heckman and Jarle Brinchmann have been able to estimate the fraction of the [OIII] and Hα luminosity attributed to AGN vs. star formation so we do have useful information on the nature of these sources (they are not ambiguous in their classification).