Mem. S.A.It. Vol. 84, 655

Memorie della

The cosmic history of black hole growth

E. Treister[1], C. M. Urry[2], and K. Schawinski[3]

[1] Universidad de Concepción, Departamento de Astronomía, Casilla 160-C, Concepción, Chile, e-mail: etreiste@astro-udec.cl
[2] Yale Center for Astronomy and Astrophysics, Department of Physics and Department of Astronomy, Yale University, P.O. Box 208121, New Haven, CT 06520, USA.
[3] Institute for Astronomy, Department of Physics, ETH Zurich, Wolfgang-Pauli-Strasse 16, CH-8093 Zurich, Switzerland

Abstract. In order to fully understand galaxy formation we need to know when in cosmic history black holes are growing more intensively, in what type of galaxies this growth is happening and what fraction of these sources are invisible at most wavelengths due to obscuration. We take advantage of the rich multi-wavelength data available in the Chandra Deep Field South (CDF-S), including the 4 Msec Chandra observations (the deepest X-ray data to date), in order to measure the amount of black hole accretion as a function of cosmic history, from $z \sim 0$ to $z \sim 6$. We obtain stacked rest- frame X-ray spectra for samples of galaxies binned in terms of their IR luminosity, stellar mass and other galaxy properties. We find that the AGN fraction and their typical luminosities, and thus black hole accretion rates, increase with IR luminosity. The integrated intensity at high energies indicates that a significant fraction of the total black hole growth, 22%, occurs in heavily-obscured systems that are not individually detected in even the deepest X-ray observations. We further investigate the AGN triggering mechanism as a function of bolometric luminosity, finding evidence for a strong connection between significant black hole growth events and major galaxy mergers from $z \sim 0$ to $z \sim 3$, while less spectacular but longer accretion episodes are most likely due to other (stochastic) processes. AGN activity triggered by major galaxy mergers is responsible for 60% of the total black hole growth.

Key words. galaxies: active — galaxies: Seyfert — galaxies: interactions — X-rays: galaxies — X-rays: diffuse background

1. Introduction

It is now clear that the formation of the supermassive black holes (mass greater than a million solar masses) that can be now found in the centers of most massive galaxies (e.g., Kormendy & Richstone 1995) is directly connected to the evolution of their host galaxies (Ferrarese & Merritt 2000; Gebhardt et al. 2000). However, the details of this connection are still not well understood. In order to fully understand galaxy formation we need to know when in the cosmic history are black holes growing more intensively, in what type of galaxies this growth is happening and what fraction of these sources are invisible at most wavelengths due to obscuration.

Send offprint requests to: E. Treister

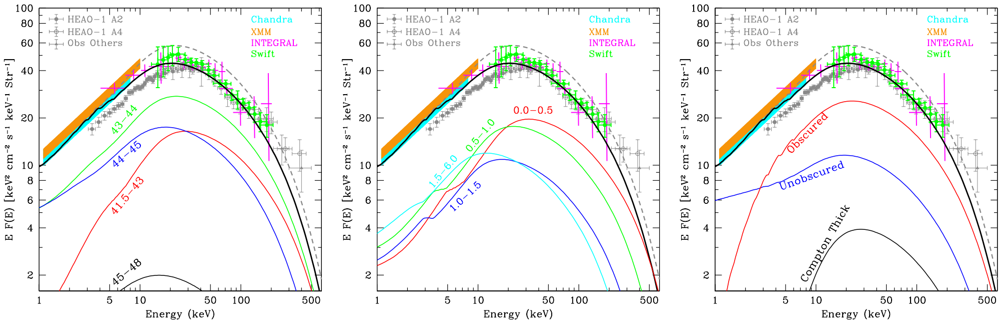

Fig. 1. Observed spectrum of the extragalactic XRB from HEAO-1 (Gruber et al. 1999), Chandra (Hickox & Markevitch 2006), XMM (De Luca & Molendi 2004), INTEGRAL (Churazov et al. 2007) and Swift (Ajello et al. 2008) data. In each panel the *thick black solid line* shows the population synthesis model for the XRB spectrum of Treister et al. (2009a). *Left panel*: Contribution to the XRB as a function of intrinsic X-ray luminosity for sources with $L_X < 10^{43}$ erg/s (*red line*), $10^{43} < L_X < 10^{44}$ (*green line*), $10^{44} < L_X < 10^{45}$ (*blue line*) and $L_X > 10^{45}$ erg/s (*thin black line*). *Center panel*: Contribution to the XRB from sources at $z < 0.5$ (*red line*), $0.5 < z < 1$ (*green line*), $1 < z < 1.5$ (*blue line*) and $z > 1.5$ (*cyan line*). *Right panel*: Contribution to the XRB from unobscured (*blue line*), obscured but Compton-thin (*red line*) and Compton-thick sources (*thin black line*).

The spectral shape and intensity of the extragalactic X-ray background (XRB) can be used as an integral constraint for the statistical properties of the Active Galactic Nuclei (AGN) population, and thus the amount of black hole growth occurring in these systems and their evolution. This is because most recent deep surveys show that ∼90% of the observed 2–8 keV XRB radiation can be attributed to resolved AGN (e.g., Hickox & Markevitch 2006).

As can be seen in Figure 1, the XRB shows that most of the BH accretion that can be traced in X-rays can be attributed to obscured but Compton-thin, moderate-luminosity systems ($L_X \sim 10^{44}$ erg/s, corresponding to $L_{bol} \sim 10^{45}$ erg/s) at relatively low redshifts ($z<1$). While the results presented here are based on the Treister et al. (2009a) XRB model, similar results are obtained if other recent computations are considered (e.g., Treister & Urry 2005; Ballantyne et al. 2006; Gilli et al. 2007). While these conclusions are certainly interesting, it is worth remembering that the XRB provides only an integral flux constraint, and therefore less obscured sources at lower redshifts carry more weight. It is certainly possible that a large fraction of the total BH accretion occurs in heavily obscured, even Compton-thick, AGN at high redshifts (Treister et al. 2009a). This is studied in more detail in the next section.

2. Hidden BH accretion

Because much of the energy absorbed at optical to X-ray wavelengths is later re-emitted in the mid to far-IR, it is expected that AGN, in particular the most obscured ones, should be very bright mid-IR sources (Treister et al. 2006). Sources having mid-IR excesses, relative to their rest-frame optical and UV emission, have been identified as potential CT AGN candidates at $z \sim 2$ (e.g., Daddi et al. 2007; Fiore et al. 2008; Treister et al. 2009b). However, because of the strong connection between vigorous star formation and AGN activity in the most luminous infrared sources (Sanders et al. 1988, and many others), the relative contribution of these two processes remains uncertain and controversial. While the majority of these IR-excess sources are not individually detected in X-rays, a significant signal is found in X-ray stacks. As shown in Fig. 2, the strong stacked detection at $E>5$ keV clearly indicates the presence of a large number of heavily-obscured AGN in this infrared-excess sub-sample. Specifically, Treister et al. (2009b) reported that heavily-obscured AGN are ~80-90% of the mid-IR-excess sources in the ECDF-S.

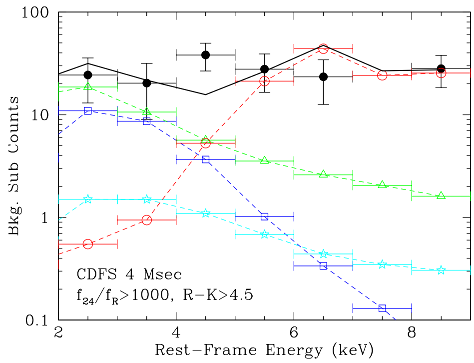

Fig. 2. Stacked background-subtracted Chandra counts as a function of rest-frame energy, for sources with f_{24}/f_R >1000 and R-K >4.5 in the 4 Msec CDF-S field (*filled circles*). The *cyan dashed lines (stars)* shows the simulated spectra for the high-mass X-ray binary (HMXB) population normalized using the relation between star-formation rate and X-ray luminosity (Ranalli et al. 2003). The *blue dashed lines (open squares)* show simulated thermal spectra corresponding to a black body with kT=0.7 keV. An absorbed AGN spectrum, given by a power-law with Γ=1.9 and a fixed N_H=10^{24} cm^{-2}, is shown by the *red dashed lines (open circles)*. In addition, a scattered AGN component, characterized by a 1% reflection of the underlying unobscured power-law, is shown by the *green dashed lines (open triangles)*. The resulting summed spectrum (*black solid lines*) is in very good agreement with the observed counts. The strong detection in the stacked spectrum at E>5 keV, confirms the presence of a significant number of heavily-obscured AGN in these IR-excess objects (Treister et al. 2009b).

Several groups (e.g, Kartaltepe et al. 2010) have found that the fraction of galaxies containing an AGN is a strong function of their IR luminosity. In Fig. 3 we show the stacked spectra for the sources in the CDF-S, grouped in bins of IR luminosity, as presented by Treister et al. (2010b). We can see by comparing these spectra that the relative emission at E≳5 keV, where we expect the AGN emission to dominate even for heavily-obscured sources, changes with IR luminosity. In other words, there is a clear trend, with stronger high energy X-ray emission at increasing IR luminosity. The spectra shown in Fig. 3 cannot be directly interpreted, as the detector-plus-telescope response information is lost after the conversion to rest-frame energy and stacking. Hence, simulations assuming different intrinsic X-ray spectra have to be used in order to constrain the nature of the sources dominating the co-added signal.

The observed stacked spectral shape cannot be explained by any plausible starburst spectrum. An AGN component dominating at E>5 keV, is required. The average intrinsic rest-frame 2-10 keV AGN luminosity needed to explain the observed spectrum, assuming that every source in the sample contains an AGN of the same luminosity, is 6×10^{42} erg s^{-1} for sources with L_{IR}>$10^{11}L_\odot$, 3×10^{42} erg s^{-1} for sources with L_{IR}>5×$10^{10}L_\odot$, 5×10^{41} erg s^{-1} for 5×$10^{10}L_\odot$>L_{IR}>$10^{10}L_\odot$ and 7×10^{41} erg s^{-1} for L_{IR}>$10^{10}L_\odot$. All of these are (intrinsically) very low-luminosity AGN; even if there is a range, it is extremely unlikely to include high-luminosity quasars like those discussed in previous stacking papers. This is not too surprising, actually, because the surveyed volume (even to high redshift) is small, so rare objects like high-luminosity quasars do not appear. If the heavily-obscured AGN in these stacked samples have the same median intrinsic luminosity as the X-ray detected sources with similar IR luminosities, this would indicate that 15% of the galaxies with L_{IR}>$10^{11}L_\odot$ contain a heavily-obscured AGN. This fraction is ~10% in the L_{IR}>5×$10^{10}L_\odot$ and 5×$10^{10}L_\odot$>L_{IR}>$10^{10}L_\odot$ samples. For sources with L_{IR}>$10^{10}L_\odot$ this fraction is <5%. This extra AGN activity (in addition to the X-ray detected sources) can account for ~22% of the total black hole accretion. Adding this to the obscured black hole growth in X-ray detected AGN (Luo et al. 2008), we confirm that most of this growth, ~70%, is significantly obscured and missed by even the deepest X-ray surveys (Treister et al. 2004, 2010a).

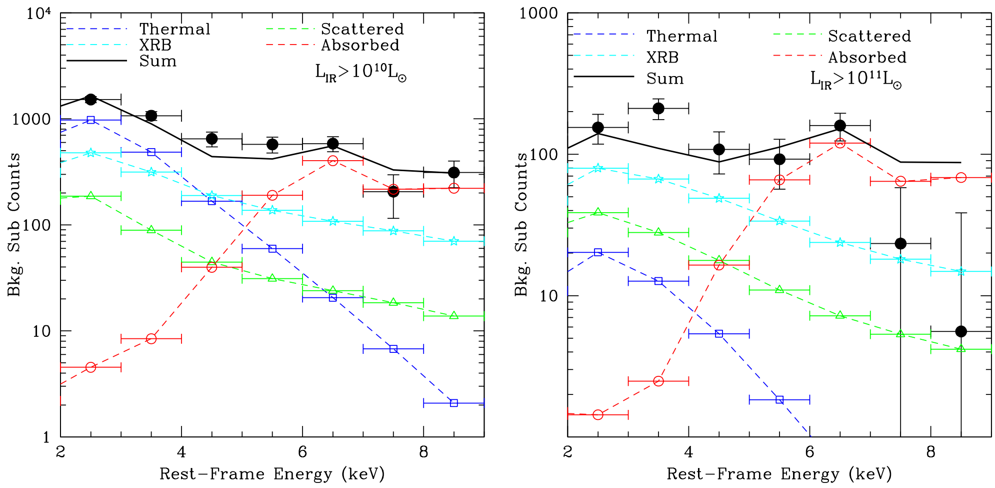

Fig. 3. Stacked background-subtracted Chandra counts as a function of rest-frame energy for sources with low (*left panel*) and high (*right panel*) IR luminosity (*black filled circles*). The *cyan dashed lines (stars)*, *blue dashed lines (open squares)*, *red dashed lines (open circles)* and *green dashed lines (open triangles)* show the same model components as in Fig. 2. The resulting summed spectra (*black solid lines*) are in very good agreement with the observed counts. The strong detection in the stacked spectrum at E>5 keV, in particular at the higher IR luminosities, confirms the presence of a significant number of heavily-obscured AGN in these samples.

3. What triggers BH growth?

While it is clear now that most galaxies contain a supermassive black hole in their center, in only relatively few cases is this black hole actively growing. This indicates that black hole growth is most likely episodic, with each luminous event lasting ~10^7-10^8 years (Di Matteo et al. 2005). Hence, an obvious question is what triggers these black hole growth episodes?

Major galaxy mergers provide a good explanation, since as simulations show, they are very efficient in driving gas to the galaxy center (Barnes & Hernquist 1991), where it can be used as fuel for both intense circumnuclear star formation and black hole growth. Indeed, a clear link between quasar activity and galaxy mergers has been seen in intensely star-forming galaxies like Ultra-luminous infrared galaxies (ULIRGs) and in some luminous quasars (e.g., Sanders et al. 1988). In contrast, many AGN are clearly not in mergers or especially rich environments (De Robertis et al. 1998) and the prevalence of disks in most AGN host galaxies rules out frequent major mergers (Schawinski et al. 2011, 2012; Simmons et al. 2012). Instead, minor interactions (Moore et al. 1996), instabilities driven by galaxy bars (Kormendy & Kennicutt 2004) and other internal galaxy processes might be responsible for these lower activity levels. Understanding the role of mergers is further complicated by the difficulty of detecting merger signatures at high redshifts.

In order to reconcile these potentially contradictory observations it has been suggested that the AGN triggering mechanism is a function of luminosity and/or redshift (Finn et al. 2001, and others). More recently, Hopkins & Hernquist (2009) used five indirect tests to conclude that the triggering mechanism is strongly luminosity-dependent and more weakly redshift-dependent, so that only the most luminous sources, which are preferentially found at z>2, are triggered by major mergers. Thanks to results from large AGN surveys, which now include heavily-obscured

IR-selected sources, and recent deep high-resolution observations carried out with the *Hubble* WFC3 detector, it is now possible to obtain reliable morphological information even for high-z, low luminosity sources.

To measure the fraction of AGN hosted by a galaxy undergoing a major merger as a function of luminosity and redshift, Treister et al. (2012) compiled information from AGN samples selected from X-ray, infrared and spectroscopic surveys. They studied data from 10 independent surveys, which include 874 AGN, spanning a wide range in luminosities, $3\times10^{42}<L_{bol}(\mathrm{erg\ s^{-1}})<5\times10^{46}$, and redshift, $0<z<3$. The goal of that work was to determine the physical mechanism(s) that provoked the AGN activity identified in these surveys. Only visual morphological classifications were used, as they are the most reliable option to determine if a galaxy is experiencing a major merger (Darg et al. 2010). The fraction of AGN linked to galaxy mergers in these samples has been computed by dividing the number of AGN in which the host galaxy has been classified as an ongoing merger or as having major disturbances by the total number of AGN. Figure 4 shows the fraction of AGN showing mergers as a function of bolometric luminosity, which increases rapidly, from ~4% at 10^{43} erg s^{-1} to ~90% at 10^{46} erg s^{-1}.

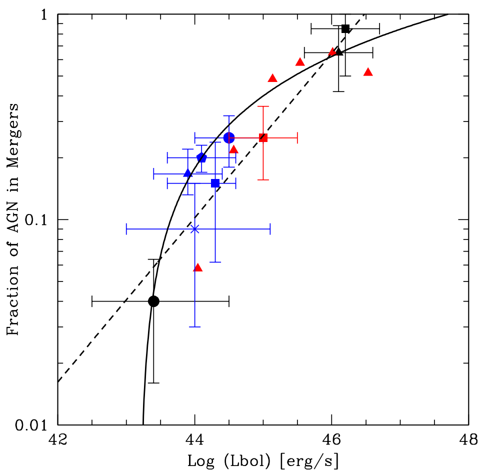

Fig. 4. Fraction of AGN showing mergers as a function of the AGN bolometric luminosity, from the work of Treister et al. (2012). Colors indicate AGN selection method (*red*: infrared, *blue*: X-rays, *black*: optical). Encircled symbols show samples at $z<1$. *Solid line* shows a fit to the data assuming a linear dependence of the fraction on log (L_{bol}), while the *dashed line* assumes a power-law dependence.

As can be concluded from Fig. 4, and was previously reported (e.g., Treister et al. 2010a), about half of the BH growth happens in quasar-like AGN following a major merger, while the other half occurs in secularly-fueled lower-luminosity AGN. At relatively high redshifts, $z\gtrsim2$, there is ~60% more black hole growth in merger-triggered AGN than in those growing via secular processes, as reported by Treister et al. (2012). At lower redshifts, there are relatively fewer galaxy mergers and so secular processes become slightly more important. Furthermore, at lower redshifts dry mergers become more common than gas-rich major mergers (Kauffmann & Haehnelt 2000). Since the availability of gas is a critical factor in determining the black hole accretion rate, this further explains why major mergers are relatively more important at high redshifts. It is interesting to note that the diminishing role of mergers coincides with the decline in the space density of black hole growth and with the observed decline in the cosmic star formation rate (Dahlen et al. 2007), i.e., cosmic downsizing. Integrated over the whole cosmic history, to z=0, 56% of the total black hole growth can be attributed to major galaxy mergers.

In terms of numbers, the population is strongly dominated by secularly-triggered AGN. Indeed, Treister et al. (2012) concluded that ~90% of the AGN at all redshifts are associated with secular processes. This explains the conclusions of previous studies, mostly based on X-ray surveys (e.g. Cisternas et al. 2011; Schawinski et al. 2010, 2011; Kocevski et al. 2012; Simmons et al. 2012) of moderate luminosity AGN, that found that normal disk-dominated galaxies constitute the majority of the AGN host galaxies. So, we conclude that while most AGN are triggered by secular processes, a slight majority of the black hole growth, particularly at high redshifts, can be attributed to intense accretion episodes linked to major galaxy mergers.

Acknowledgements. We thank the organizers of the interesting and stimulating X-ray Astronomy: the next 50 years conference! In particular, ET would like to thank them for the opportunity to give an invited talk. Support for the work of ET is provided by the Center of Excellence in Astrophysics and Associated Technologies (PFB 06), by the FONDECYT grant 1120061 and by the Anillo project ACT1101.

References

Ajello, M. et al. 2008, ApJ, 689, 666
Ballantyne, D. R., Everett, J. E., & Murray, N. 2006, ApJ, 639, 740
Barnes, J. E. & Hernquist, L. E. 1991, ApJ, 370, L65
Churazov, E. et al. 2007, A&A, 467, 529
Cisternas, M., et al. 2011, ApJ, 726, 57
Daddi, E. et al. 2007, ApJ, 670, 173
Dahlen, T., et al. 2007, ApJ, 654, 172
Darg, D. W., et al. 2010, MNRAS, 401, 1552
De Luca, A. & Molendi, S. 2004, A&A, 419, 837
De Robertis, M. M., Yee, H. K. C., & Hayhoe, K. 1998, ApJ, 496, 93
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Nature, 433, 604
Ferrarese, L. & Merritt, D. 2000, ApJ, 539, L9
Finn, R. A., Impey, C. D., & Hooper, E. J. 2001, ApJ, 557, 578
Fiore, F. et al. 2008, ApJ, 672, 94
Gebhardt, K. et al. 2000, ApJ, 539, L13
Gilli, R., Comastri, A., & Hasinger, G. 2007, A&A, 463, 79
Gruber, D. E., Matteson, J. L., Peterson, L. E., & Jung, G. V. 1999, ApJ, 520, 124
Hickox, R. C. & Markevitch, M. 2006, ApJ, 645, 95
Hopkins, P. F. & Hernquist, L. 2009, ApJ, 694, 599
Kartaltepe, J. S. et al. 2010, ApJ, 709, 572
Kauffmann, G. & Haehnelt, M. 2000, MNRAS, 311, 576
Kocevski, D. D., et al. 2012, ApJ, 744, 148
Kormendy, J. & Kennicutt, Jr., R. C. 2004, ARA&A, 42, 603
Kormendy, J. & Richstone, D. 1995, ARA&A, 33, 581
Luo, B. et al. 2008, ApJS, 179, 19
Moore, B., et al. 1996, Nature, 379, 613
Ranalli, P., Comastri, A., & Setti, G. 2003, A&A, 399, 39
Sanders, D. B., et al. 1988, ApJ, 325, 74
Schawinski, K., et al. 2012, MNRAS, 425, L61
Schawinski, K., et al. 2011, ApJ, 727, L31
Schawinski, K. et al. 2010, ApJ, 711, 284
Simmons, B. D., et al. 2012, ApJ, 761, 75
Treister, E., et al. 2010a, Science, 328, 600
Treister, E., Schawinski, K., Urry, C. M., & Simmons, B. D. 2012, ApJ, 758, L39
Treister, E. & Urry, C. M. 2005, ApJ, 630, 115
Treister, E., Urry, C. M., Schawinski, et al. 2010b, ApJ, 722, L238
Treister, E., et al. 2006, ApJ, 640, 603
Treister, E., Urry, C. M., & Virani, S. 2009a, ApJ, 696, 110
Treister, E. et al. 2004, ApJ, 616, 123
Treister, E. et al. 2009b, ApJ, 706, 535