Multiwavelength perspective of AGN evolution

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Abstract.
Discovering and studying obscured AGN at $z \gtrsim 1 - 3$ is important not only to complete the AGN census, but also because they can pinpoint galaxies where nuclear accretion and star-formation are coeval, and mark the onset of AGN feedback. We present the latest results on the characterization of $z=1-3$ galaxies selected for their high mid-infrared to optical flux ratio, showing that they are massive and strongly star-forming galaxies, and that many do host highly obscured AGN. We present a pilot program to push the search of moderately obscured AGN up to $z=5-6$ and discuss the perspectives of this line of research.

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INTRODUCTION

Understanding how galaxies formed and how they become the complex systems we observe in the local Universe is a major theoretical and observational effort, mainly pursued using multi-wavelength surveys. We know today that tight links must exist between super-massive black holes (SMBHs) found at the centre of bulgy galaxies and their host galaxies. We also know that most SMBH growth is due to accretion of matter during their active phases, implying that most bulges went through a strong AGN phase to produce the SMBH/galaxy mass ratio of $\sim 0.001$ observed today. The co-evolution of galaxies and their SMBH depends on some physical mechanism (‘feedback’ hereafter) linking accretion and ejection occurring on sub-parsec scale in galaxy nuclei to the rest of the galaxy. AGN feedback is often invoked to explain the observed galaxy colors. In the SMBH-galaxy co-evolutionary sequence the phase when a galaxy is found in a passive status is preceded by a powerful active phase, when cold gas is available for both star-formation and nuclear accretion. The same cold gas and dust can intercept the line of sight to the nucleus, and therefore a natural expectation of this scenario is that the early, powerful AGN phase is also highly obscured. Once a SMBH reaches masses $> 10^{7-8}M_\odot$, the AGN can heat efficiently the interstellar matter through winds, shocks, and high-energy radiation, thus inhibiting further accretion and star-formation and making the galaxy colors redder. At the end of this phase an unobscured, type 1 AGN shines, while its host galaxy becomes progressively red. Once most of the original cold gas is expelled from the system, nuclear accretion and SF can occur only thanks to gas and dust in stellar winds and/or accretion of fresh gas cooling from haloes, and we are left with a passive or low star-forming galaxy, hosting a relic SMBH or a low luminosity nucleus. While most known systems are observed at the end of feedback processes, i.e. in the two latter phases, the investigation of the coeval phase of obscured black hole accretion and star-formation at $z \gtrsim 1 - 3$, the peak of nuclear and stellar activity([3, 2, 26]
and references therein), can give crucial information on AGN feedback when it is in action. Current X-ray surveys can select efficiently moderately obscured AGN up to \(z=2-3\). Highly obscured AGN at the same redshifts can be recovered thanks to the dust reprocessing of the AGN UV emission in the infrared, by selecting sources with mid-IR (and/or radio) AGN luminosities but faint, host galaxy dominated, near-IR and optical emission [25, 29, 9, 12, 10, 13]. All these studies are based on Spitzer data, and were able to discover a population of highly obscured AGN up to \(z \sim 3\). We summarize in Section 2 the latest results on this topic.

Pushing this research up to the epoch of formation of the first galaxies/SMBH at \(z \gtrsim 3 - 4\) is clearly the next step. This may allow one to assess the role of nuclear activity and AGN feedback in the assembling of the first structures, and consequently to attack the following fundamental problems. First, optical surveys have discovered luminous QSOs at \(z > 6\) with SMBHs of \(M > 10^9 M_\odot\), which would imply bulges of \(> 10^{12} M_\odot\) already formed less than 1 Gyr after the Big Bang, if the local SMBH/galaxy mass ratio should hold at those epochs. It is likely that the local SMBH/galaxy relationship breaks down at some redshift, and indeed some indications of this do exist [2, 27, 19]. But when? and how? Second, early AGN activity can contribute to the reionization and can heat the intergalactic medium, therefore affecting further structure formation. Obtaining a complete AGN census at high-z is crucial to tackle these issues. High-z AGN can however play a crucial role also in other issues. Structure formation and evolution at high-z is naturally affected by the expansion rate of the Universe at that epoch. For example, a fast expansion rate at high-z may leave too little time to form large structures, while a slow expansion rate may imply a large amount of high-z galaxies and SMBHs. Therefore, sensitive surveys of high-z galaxies and AGN may provide strong constraints to the expansion rate of the Universe at early times. The obvious problem is how to disentangle subtle cosmological effects from complex baryon physics. The best strategy is to target quickly growing structures, in particular structures growing exponentially, so that little differences in the time of expansion of the Universe can be significantly emphasized. SMBHs are the cosmic structures with the fastest growth rate and this suggests using them to constrain AGN feeding and accretion physics at high-z and to test and/or constrain cosmological scenarios. We present in Section 3 preliminary results on the search for high-z AGN in X-rays and discuss the perspectives of this line of research.

**PROBING THE PHASE OF SMBH/GALAXY COMMON GROWTH: HIGHLY OBSCURED AGN AT Z \(\sim 1 – 3\)**

Deep Spitzer surveys, accompanied by high quality multiwavelength observations, have unveiled a large population of galaxies with high mid-infrared to optical flux ratio (\(F(24 \mu m)/F(R) > \text{several hundreds}\)) and high redshift (\(z \sim 1 – 3\), [12, 10, 13]). These galaxies are often dubbed Dust Obscured Galaxies or “DOGs”. They are young, massive and star-forming galaxies. Fig. 1, left panel, shows the stellar mass distribution of DOGs from the COSMOS and GOODS-MUSIC samples \(F(24 \mu m)/F(R) > 300, R-K > 4.5\). The stellar mass has been evaluated from the rest frame 1\(\mu m\) luminosity for the COSMOS MIPS-bright sample \((F(24 \mu m) > 550 \mu Jy)\) and from a proper SED fitting for the GOODS-MUSIC sample [31]. Fig. 1 right panel shows the distribution of the star-
FIGURE 1. Left panel: the stellar mass distribution of DOGs from the COSMOS MIPS-bright sample (this solid line) and GOODS-MUSIC samples in two F(24 µm) bins: 160 < F(24 µm) < 400 µJy (long dashed line); 20 < F(24 µm) < 160 µJy (short dashed line). Right panel: the star-formation rate distribution of GOODS-MUSIC DOGs with F(24 µm) > 160 µJy (long dashed line); 20 < F(24 µm) < 160 µJy (thin solid line). The stellar mass and star-formation rate (SFR) distributions of the entire GOODS-MUSIC sample with F(24 µm) > 20 µJy are shown for comparison in the respective panel (thick solid lines).

formation rate for the GOODS-MUSIC DOGs. Note that the DOGs distributions are skewed towards higher values of both stellar mass and SFR compared to the galaxy population with F(24 µm) > 20 µJy. The majority of DOGs with F(24 µm) > 160 µJy have stellar mass > 10^{11} M_\odot and SFR > 40 M_\odot/yr. Many DOGs have SFR of several hundreds or even thousands M_\odot/yr. Similar results on masses and SFRs have been recently obtained[10, 7]. Several authors found that a substantial fraction of DOGs hosts an active nucleus, based on optical or mid-infrared spectroscopy[25, 17, 33, 34]. However, DOGs are usually faint X-ray sources in deep or even ultra-deep X-ray observations. These facts suggest that DOGs often host active nuclei that are highly obscured, nuclei covered by column densities in excess to \sim 10^{24} cm^{-2}. Such high column density strongly reduce the AGN hard X-ray flux, making them difficult to study individually in X-rays. Nevertheless, DOGs are detectable in deep Chandra surveys by stacking together the X-ray images at the source position. This technique increases the exposure time by tens to hundreds of times, and by a factor about square root of this number the sensitivity and the flux limit. By using this technique we were able to constrain the X-ray spectrum of DOGs in the GOODS-MUSIC and COSMOS MIPS-bright samples, discovering hard X-ray colors. By comparing these colors to the expectations of Monte Carlo simulations, including spectral distributions of both star-forming galaxies and obscured AGN, we constrained the highly obscured AGN fraction in the COSMOS-MIPS bright DOGs with F(24 µm)/F(R) > 300 and > 1000 to > 60% and > 90% respectively[13]. Of course this is a statistical results, valid on average for the sample, and valid if the assumptions in the Monte Carlo simulations are correct. The most critical assumption is the shape of the X-ray spectrum of purely star-forming galaxies. We assumed, in agreement with X-ray observations of nearby star-forming galaxies, a power law spectrum with energy index \alpha_E = 0.9 in the band 1-20 keV, which corresponds to the observed band 0.3-6 keV at a typical redshift of 2. In local galaxies the spectrum is dominated by the
emission of low mass X-ray binaries, which constitute about 80% of the population of luminous X-ray sources. High mass X-ray binaries, HMXB, have a significantly flatter spectrum ($\alpha_E = 0.2 \pm 0.2$) and their fraction may well be higher in young star-forming galaxies [28]. In particular, their fraction may be significantly higher if the galaxy IMF is skewed toward high stellar mass values. We note however that the X-ray color measured for the COSMOS MIPS sources with $F(24 \mu m)/F(R) > 1000$ and 300 corresponds to an inverted spectrum with $\alpha_E = -0.5$ and to $\alpha_E = 0$ respectively, quite extreme values even for galaxies with X-ray emission completely dominated by HMXB. If DOGs do not host highly obscured AGN their extremely hard X-ray color would put constraints on their binary population, and therefore on the galaxy IMF. The cleanest way to identify a highly obscured AGN is through X-ray and/or optical spectroscopy. The smoking gun of such AGN is a strong (equivalent width $EW > \sim 1$ keV) iron Kα line. Furthermore, strong high ionization lines such as [NeV] must also be present in the optical spectra, together with the absence of broad lines. To investigate further the nuclear properties of DOGs we have therefore undertaken both lines of research.

Rest frame X-ray spectroscopy of DOGs

DOGs are faint X-ray sources and therefore direct X-ray spectroscopy is feasible only for the brightest sources, i.e. DOGs in the SWIRE survey [29, 20]. Most CDFS and COSMOS DOGs are too faint to extract useful X-ray spectral information from individual sources. However, we may again resort to stacking techniques to increase sample exposure time and sensitivity. To this purpose we stacked together the X-ray counts of 99 COSMOS MIPS-bright sources with $F(24 \mu m)/F(R) > 300$ and R-K > 4.5 in 1 keV wide rest frame bands, from 1 to 8 keV. We limited the analysis to sources with less than 10 X-ray counts, to exclude unobscured and moderately obscured AGN and to make sure that the stacks are not dominated by a few bright sources. We also limited the analysis to sources in the redshift range 0.7-3, for which the iron Kα line is observed at energies between 1.6 and 3.8 keV, with reasonably constant efficiency. Fig. 2 shows the stacked Chandra images around the 99 COSMOS DOGs at 6 rest frame energies, and the spectrum obtained by extracting the counts from circular regions of 2 arcsec radius around the centers of these images. The DOGs are detected with a signal to noise 3 and 3.5 in the 3-4 keV and 6-7 keV bands respectively. Note as the signal is stronger in the 6-7 keV band, which include the iron Kα line, in comparison to the nearby 5-6 keV and 7-8 keV bands (signal to noise 1.4 and 1.5 respectively). Since the width of the energy bins is 1 keV, only lines with $EW > \sim 1$ keV would provide a signal. We conclude that the detection of COSMOS DOGs at 6-7 keV and not at nearby energies suggests the presence of strong Kα lines in a large fraction of these sources.

Optical spectroscopy of DOGs

29 of the 171 COSMOS MIPS-bright sources with $F(24 \mu m)/F(R) > 300$ and R-K > 4.5 have zCOSMOS and Magellan/IMACS optical spectra covering the [NeV] line (but
only 3 more extreme sources with F(24μm)/F(R)>1000). We studied these spectra to search for high ionization lines, indicative of AGN activity[11]. We detected [NeV] emission with EW=2-15Å in 10 sources, 5 with relatively bright X-ray counterparts in the Chandra-COSMOS catalog[8], and therefore likely moderately obscured AGN, and 5 in DOGs without a direct X-ray emission. The upper limits to the [NeV] equivalent width are lower than 2-3Å in 7 sources (5 without direct X-ray detection). We conclude that ∼50% of the COSMOS DOGs with F(24μm)/F(R)>300 and with optical spectra of quality good enough to detect [NeV] do show AGN-like [NeV] emission, a fraction consistent with the result of the Chandra stacking analysis[13]. We will more than double the number of COSMOS DOGs with optical spectroscopy in the near future thanks to additional zCOSMOS and IMACS spectra acquired in the course of 2008-2009, and to new Keck/DEIMOS spectroscopy currently on going.

### PUSHING TOWARD HIGHER REDSHIFTS

Joining current X-ray and infrared surveys will allow a sufficiently robust determination of the luminosity function (LF) of all AGN, regardless of the level of obscuration, and consequently the determination of the full AGN census, up to z∼ 3. At higher redshifts the situation is much more complex. The search of highly obscured AGN at z> 3 is today cumbersome, because of the limited sensitivity of Spitzer for faint high-z sources. The selection of large samples of highly obscured AGN at high z must probably await the advent of JWST, with its factor of ∼ 100 improvement in sensitivity in infrared imaging/spectrometry with respect to Spitzer, and ALMA, with its spectroscopy capability. Thanks to the strong negative K-correction at (sub-)mm wavelengths, ALMA may detect star-forming galaxies at z>5 as easily as at z∼ 1, regardless of the presence of an AGN, and regardless of its obscuration. Hence ALMA may deliver a truly unbiased sample of AGN. The AGN identification will be achieved through the detection of molecular lines (such as HCN and HCO+), predominantly produced in "X-ray dominated regions" that typically surround AGN[23]. On the other
hand, large area optical surveys such as the SDSS have already been able to discover large samples of $z > 4.5$ QSOs\cite{30} and about 40 QSOs at $z > 5.7$\cite{16}. The majority of the high-z SDSS AGN are broad line, unobscured, high luminosity AGN. They are likely the tips of the iceberg of the high-z AGN population. Lower luminosity and/or moderately obscured AGN can, in principle, be detected directly in current X-ray surveys. Unfortunately, so far the number of X-ray selected AGN at $z > 3$ is only of a few tens, and $\sim$half a dozen at $z > 4.5$ (see e.g. \cite{4, 14, 5, 6}). The difficulty in detecting directly high-z AGN in X-ray surveys suggests an alternative approach. Looking at the X-ray emission at the position of known sources allows one to a) use a less conservative threshold for source detection than in a blind search, and therefore to reach a lower flux limit, and b) apply stacking techniques\cite{21, 1}.

As an experiment, we used the full 2 Ms exposure of the CDFS to look at the X-ray emission at the position of $\sim 5000$ $z > 2$ galaxies drawn from the GOODS-MUSIC catalog\cite{15}. To keep the number of spurious X-ray detections small, we set the probability threshold for a background fluctuation to $P = 2 \times 10^{-4}$. First, an average background spectrum was accumulated at three different off-axis angles, by excluding bright sources\cite{22}. The inner background spectra show a stronger low energy cut-off, due to a thicker deposition of contaminants at the centre of the ACIS-I 4 chip region. Background at the position of each source was then evaluated by normalizing the average background at the source off-axis to the source spectrum accumulated above 7 keV, where the contribution of faint sources is negligible, due to the sharp decrease of the mirror effective area. We then computed the Poisson probability that the counts accumulated below 7 keV are a fluctuation of this background. We optimized the source detection both for the source extraction area and for the energy band. We finally converted the count rates in each detection band into 0.5-2 keV count rates by assuming a power law model with $\alpha_E = 0.4$. Assuming other reasonable spectral shapes changes the conversion factor by $\lesssim 30\%$, thanks to the fact that the chosen reference band is rather narrow. Using this technique we detected 33 $z > 3$ galaxies in the GOODS-MUSIC area, 15 of which are not present in previous catalogs based on blind searches\cite{22} (10 galaxies with a spectroscopic redshift). 5 galaxies have $z > 4.5$ (1 spectroscopic redshift).

We combined this high-z sample to the Chandra-COSMOS sample\cite{8} to compute the high-z AGN number density and LF shown in Fig. 3. We plot in the same Fig. three optically selected AGN LF, after converting the optical/UV luminosities to X-ray luminosities following\cite{24}. We note that first most of the CDFS and COSMOS $z > 3$ AGN are moderately obscured, based on a hardness ratio analysis. They may well be missed in optical surveys. Second, the X-ray LF extends the SDSS determination by $\sim 2$ decades toward lower luminosities, reaching the regime of Seyfert-like AGN at $z=5$. Third, our determination at low luminosity is nominally a factor $\sim 3 - 5$ higher than that of Fontanot et al. (2007), although consistent with it within the large error-bars. Reducing these error-bars is therefore mandatory. Doubling the present CDFS and COSMOS exposure times would produce error-bars comparable to those of optically selected surveys (Fig.3, right panel).
CONCLUSIONS

Optical spectroscopy of COSMOS MIPS-bright DOGs with F(24µm)/F(R)>300 and a rest frame stacking analysis of their faint Chandra counterparts confirm that >50% do host a highly obscured active nucleus, in agreement with[13]. DOGs are massive, star-forming galaxies at z=1-3. They represent a class of high-z galaxies where star-formation and nuclear accretion are coeval, i.e. objects where AGN feedback is in action, and it has not yet significantly quenched star-formation. Sub-millimiter galaxies share the same characteristics[2] and have similar space densities[2, 13]. DOGs observations at mm wavelength with present and future (ALMA) facilities may be able to find the observational signature of outflows on galaxy scales, and therefore of on going AGN feedback, through spectroscopy of molecular lines.

We are starting to push the search for moderately and highly obscured AGN up to the epoch of formation of the first galaxies/SMBH, i.e. up to z=6. Aggressive multiband data analysis strategies, fully exploiting the synergies between optical/infrared and X-ray deep surveys, can significantly increase the number of X-ray selected AGN at high-z. Our pilot program on the CDFS 2 Msec observation nearly doubled the number of z > 3 AGN detected in X-rays in the GOODS-MUSIC area. Doubling the current Chandra exposure times on the CDFS and COSMOS area will allow us to nearly triple the current sample of high-z AGN in these surveys, which in turn will produce error bars comparable to those of the z > 6 QSO in the SDSS (see Fig. 3). A program to double the Chandra exposure of the CDFS has been recently approved by the CXO director, and these data will be available in the next few years. By joining the X-ray and SDSS selected high-z AGN will allow us to constrain both the z > 4.5 normalization of the AGN LF and its slope over a wide luminosity interval (more than 3 decades). At z=5-6 the SMBH mass growth is an extremely steep function of the efficiency of conversion of gravitational potential into radiation $\varepsilon$. Since at such high-z it is reasonable to assume that nuclear accretion proceeds at its Eddington value, this means that also the AGN luminosity is a
steep function of $\varepsilon$. This suggests that the slope of the AGN LF at high-z can be used to constrain the $\varepsilon$ and thus the black hole spin[32, 18]. Once fixed the BH spin distribution through the measure of the slope of the AGN LF, the normalization of the AGN LF may be used to constrain the expansion rate of the Universe at early times, and therefore distinguish between competing cosmological scenarios (Lamastra et al. in preparation).

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