ACTIVE GALACTIC NUCLEI CLUSTERING IN THE LOCAL UNIVERSE: AN UNBIASED PICTURE FROM \textit{SWIFT-BAT}

\textbf{N. Cappelluti}\textsuperscript{1}, M. Ajello\textsuperscript{2,3}, D. Burlon\textsuperscript{1}, M. Krumpe\textsuperscript{4}, T. Miyaji\textsuperscript{5,7}, S. Bonoli\textsuperscript{6}, and J. Greiner\textsuperscript{1}

\textsuperscript{1} Max Planck Institut für Extraterrestrische Physik, D-85478 Garching, Germany
\textsuperscript{2} SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA
\textsuperscript{3} KIPAC, 2575 Sand Hill Road, Menlo Park, CA 94025, USA
\textsuperscript{4} University of California, Center for Astrophysics and Space Sciences, San Diego, 9500 Gilman Dr., La Jolla, CA 92037, USA
\textsuperscript{5} Instituto de Astronomía, Universidad Nacional Autónoma de México, Ensenada, México—P. O. Box 439027, San Ysidro, CA 92143, USA
\textsuperscript{6} Max Planck Institut für Astrophysik, D-85478 Garching, Germany

Received 2010 January 28; accepted 2010 May 24; published 2010 June 4

\section*{ABSTRACT}

We present the clustering measurement of hard X-ray selected active galactic nuclei (AGNs) in the local universe. We used a sample of 199 sources spectroscopically confirmed, detected by \textit{Swift-BAT} in its 15–55 keV all-sky survey. We measured the real space projected autocorrelation function (ACF) and detected a signal significant on projected scales lower than 200 Mpc $h^{-1}$. We measured a correlation length of $r_0 = 5.56^{+0.49}_{-0.43}$ Mpc $h^{-1}$ and a slope $\gamma = 1.64^{+0.07}_{-0.08}$. We also measured the ACF of Type I and Type II AGNs and found higher correlation length for Type I AGNs. We have a marginal evidence of luminosity dependent clustering of AGNs, as we detected a larger correlation length of luminous AGNs than that of low-luminosity sources. The corresponding typical host dark matter halo masses of \textit{Swift-BAT} are $\sim \log(M_{DMH}) \sim 12$–14 $h^{-1} M_\odot$, depending on the subsample. For the whole sample, we measured $\log(M_{DMH}) \sim 13.15 h^{-1} M_\odot$ which is the typical mass of a galaxy group. We estimated that the local AGN population has a typical lifetime $\tau_{AGN} \sim 0.7$ Gyr, it is powered by supermassive black hole with mass $M_{BH} \sim (1–10) \times 10^8 M_\odot$ and accreting with very low efficiency, $\log(\epsilon) \sim -2.0$. We also conclude that local AGN host galaxies are typically red-massive galaxies with stellar mass of the order $(2–80) \times 10^{10} h^{-1} M_\odot$. We compared our results with clustering predictions of merger-driven AGN triggering models and found a good agreement.

\textit{Key words:} dark matter – diffuse radiation – galaxies: active – large-scale structure of universe – X-rays: galaxies

\textit{Online-only material:} color figures

\section*{1. INTRODUCTION}

It is now commonly believed that almost all galaxies host a central supermassive black hole (SMBH). Dynamical evidence show that the mass of the central BHs are closely linked to the mass as well as the stellar velocity dispersion of the bulge component of the host galaxy (Kormendy & Richstone 1995; Magorrian et al. 1998). This suggests that the formation and evolution of the spheroidal component of galaxies and their SMBHs are closely connected. It is of utmost importance to understand the mechanism of funneling interstellar gas into the vicinities of the SMBH, triggering the accretion. Galaxy mergers or tidal interaction between close pairs may have played a major role (Hopkins et al. 2007); furthermore, some mechanism internal to the galaxy, like galaxy disk instability may be important. Clustering properties of active galactic nuclei (AGNs) in various redshifts give an important clue to understanding which of these mechanisms trigger AGN activities in what stage of the evolution of the universe, through, e.g., the mass of the dark matter halos (DMH) in which they reside, which is linked to BH mass lifetime and Eddington rate. Measurements of the AGN clustering show that AGNs are typically hosted by DMH with a mass of the order of $\log(M) \sim 12.0–13.5 M_\odot$ (Yang et al. 2006; Miyaji et al. 2007; Gilli et al. 2009; Coil et al. 2009; Hickox et al. 2009; Krumpe et al. 2010). However, these measurements have been produced by using AGN samples obtained by optical and soft X-ray (i.e., 0.5–10 keV) surveys. Optical and soft X-ray selections miss a major part of the SMBH accretion. In the optical band, the selection of AGNs is biased by galaxy starlight dilution and by dust absorption. Although luminous soft X-ray emission is a signature of the presence of an AGN, absorbed sources can be missed with a soft X-ray selection, either because they are intrinsically less luminous (Hasinger 2008) or because of the high column density. However, X-ray emission from these sources leaks out at higher energies (i.e., >5–10 keV) where the efficiency of instruments mounting X-ray focusing optics is low. For this reason, hard X-ray selected samples could provide clean and unbiased samples of AGNs. The \textit{Swift-BAT} all-sky survey provides a spectroscopically complete (100\%) sample of local AGNs detected in the 15–55 keV energy band, with an unprecedented depth and characterization of the source properties, from redshifts to column densities. In this Letter, we present the first study of clustering of hard X-ray selected AGNs in the local universe. Throughout this Letter, we will assume a $\Lambda$-CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 100h^{-1}$ km s$^{-1}$ Mpc, and $\sigma_8 = 0.8$. Unless otherwise stated, errors are quoted at the 1$\sigma$ level.

\section*{2. THE SAMPLE OF \textit{SWIFT-BAT} HARD X-RAY SELECTED AGNs}

The Burst Alert Telescope (BAT; Barthelmy et al. 2005) on board the \textit{Swift} satellite (Gehrels et al. 2004) represents a major improvement in sensitivity for imaging the hard X-ray sky. BAT is a coded mask telescope with a wide field of view (FOV, $120^\circ \times 90^\circ$ partially coded) aperture sensitive in the 15–200 keV domain. Thanks to its wide FOV and its pointing strategy, BAT continuously monitors up to 80\% of the sky every day achieving, after several years of survey, deep exposure in the entire sky.
Results of the BAT survey (Markwardt et al. 2005; Ajello et al. 2008; Tueller et al. 2010) show that BAT reaches a sensitivity of $\sim 1$ mCrab$^8$ in 1 Ms of exposure.

The sample used in this work consists of 199 non-blazar AGNs detected by BAT during the first three years and precisely between 2005 March and 2008 March. This sample is part of the one used in Ajello et al. (2009) which comprises all sources detected by BAT at high ($|b|>15^\circ$) Galactic latitude and with a signal-to-noise ratio $(S/N)$ exceeding 5$\sigma$. The reader is referred to Ajello et al. (2009) for more details about the sample and the detection procedure. The flux limit at each direction in the sky has been computed, following Ajello et al. (2008), analyzing the local background around that position. For each source, we use the redshift already provided in Ajello et al. (2009) and the measurement of the absorbing column density as determined by a distance $d_n = n/(1 + \xi)$, where $n$ is the mean space density. A known effect when measuring pairs separations is that the peculiar velocities combined with the Hubble flow may cause a biased estimate of the distance when using the spectroscopic redshift. To avoid this effect, we computed the projected ACF (Davis & Peebles 1983):

$$w(r_p) = 2 \int_0^{\pi_{\text{max}}} \xi(r_p, \pi) d\pi,$$

where $r_p$ is the distance component perpendicular to the line of sight and $\pi$ parallel to the line of sight (Fisher et al. 1994). It can be demonstrated that, if the ACF is expressed as $\xi(r) = (r/r_0)^{-\gamma}$, then

$$w(r_p) = A(\gamma) r_p^{-\gamma-1},$$

where $A(\gamma) = (1/2)\Gamma(\gamma - 1)/\Gamma(\gamma/2)$ (Peebles 1980).

The ACF has been estimated by using the minimum variance estimator described by Landy & Szalay (1993):

$$\xi(r_p, \pi) = \frac{DD - 2DR + RR}{RR},$$

where DD, DR, and RR are the normalized number of data--data, data--random, and random--random source pairs, respectively. Equation (2) indicates that an accurate estimate of the distribution function of the random samples is crucial in order to obtain a reliable estimate of $\xi(r_p, \pi)$. Several observational biases must be taken into account when generating a random sample of objects in a flux limited survey. In particular, in order to reproduce the selection function of the survey, one has to carefully reproduce the space and flux distributions of the sources, since the sensitivity of the survey in not homogeneous on the sky. Simulated AGNs were randomly placed on the survey area. In order to reproduce the flux distribution of the real sample, we followed the method described in Mullis et al. (2004). The cumulative AGN log$N$–log$S$ source count distribution, in the 15–55 keV band, can be described by a power law, $S = kS^{-\alpha}$, with $\alpha \sim 1.55$ (Ajello et al. 2008). Therefore, the differential probability scales as $S^{-(-\alpha+1)}$. Using a transformation method, the random flux above a certain X-ray flux $S_{\lim}$ is distributed as $S = S_{\lim}(1-p)^{-\gamma}$, where $p$ is a random number uniformly distributed between 0 and 1 and $S_{\lim} = 7.6 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. All random AGNs with a flux lower than the flux limit map at the source position were excluded. Redshifts were randomly drawn from the smoothing of the real redshift distribution with a Gaussian kernel with $\sigma_r = 0.3$. An important choice for obtaining a reliable estimate of $w(r_p)$ is to set $\pi_{\text{max}}$ in the calculation of the integral above. One should avoid values of $\pi_{\text{max}}$ too large since they would add noise to the estimate of $w(r_p)$. If, instead, $\pi_{\text{max}}$ is too small one could not recover all the signal. We have calculated $w(r_p)$ by varying $\pi_{\text{max}}$ and found that the result converges at $\pi_{\text{max}} \sim 60$ Mpc $h^{-1}$. Errors on $w(r_p)$ were computed with a bootstrap resampling technique with 100 realizations. It is worth noting that in the literature, several methods are adopted for error estimates in two-point statistics, and no one has been proved to be the most precise. However, it is known that Poisson estimators generally underestimate the variance because they do consider that points

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$^8$ 1 mCrab in the 15–55 keV band corresponds to $1.27 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$.

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in ACF are not statistically independent. Jackknife resampling method, where one divides the survey area in many sub-fields and iteratively re-computes correlation functions by excluding one sub-field at a time, generally gives a good estimates of errors. But it requires that sufficient number of almost statistically independent sub-fields. This is not the case for our small sample. For these reasons, we used the bootstrap resampling for the error estimates which, in our case, are comparable with the Poisson errors.

4. RESULTS

We show in Figures 2 the projected ACF measured on the whole AGN sample of the survey. The ACF has been evaluated in the projected separation range $\sim 0.2 \text{ Mpc} h^{-1} < r_p < 200 \text{ Mpc} h^{-1}$ and has been plotted in form of $w(r_p)/r_p$ in order to reproduce the slope of $\xi(r)$ (see above). The bin size for computing $w(r_p)$ has been set to $\Delta \log(r_p, \pi) = 0.15$. We obtained an estimate of $w(r_p)$ with a significance of the order 4$\sigma$–5$\sigma$. In order to evaluate the power of the clustering signal, we fitted $w(r_p)$ with $\chi^2$ minimization technique by using Equation (1) as a model with $r_0$ and $\gamma$ as free parameters. The correction due to the integral constraint (Peebles 1980) is estimated to be much smaller than the statistical uncertainties in our sample, and thus has not been made. As a result, we obtained $r_0 = 5.56^{+0.49}_{-0.42} \text{ Mpc} h^{-1}$ and $\gamma = 1.64^{+0.08}_{-0.07}$. The confidence contours of the fit are presented in Figures 2.

We also measured the ACF for different data subsamples. We first divided the sample according to the column density: we defined as Type II AGN (or absorbed) sources with $\log(N_H) \geq 22 \text{ cm}^{-2}$ and as Type I AGN (or unabsorbed) sources if $\log(N_H) < 22 \text{ cm}^{-2}$. As a result, we constructed a sample of 96 Type I AGNs and one of 103 Type II AGNs. For both samples, we computed the ACF with the technique described above. We also split the sample into high- and low-luminosity subsamples. All the sources with $L_{15–55} > 43.2 \text{ erg s}^{-1}$ (i.e., the median luminosity of the whole sample, HL sources) were classified as high luminous, while the sources with $L_{15–55} < 43.2 \text{ erg s}^{-1}$ (LL sources) as low-luminosity sources. The results of the measurement of the ACF as a function of the source type and luminosity class are presented in Figures 2 together with the fit confidence contours. Note that for the HL sample, the fit parameters are poorly constrained because of the lack of close pairs in the sample. We also repeated the fit by freezing $\gamma$ to 1.7, and obtained consistent results (Table 1).

A summary of the fit results of all the samples used here is given in Table 1. Type I AGNs show a larger correlation with respect to that of type II AGNs, the significance of this difference is of the order $\sim 2\sigma$–3$\sigma$. HL AGNs show a 1.7$\sigma$–4.6$\sigma$ higher correlation length with respect to LL AGNs. We also checked the correlation between $r_0$ and $<L_X>$ of all the subsamples and found a linear correlation coefficient $R = 0.95$, which corresponds to a $\sim 2\sigma$ significant correlation. We can use the weighted mean dispersion of the results on the measurement of $r_0$ in our subsamples to estimate the impact of sample variance on our results under the assumption that this is the main reason of the fluctuations. Our estimates suggest that overall our results are affected by this effect at $\sim 10\%$ level. It is worth to

![Figure 2](image-url)
note that our results are more significant than those obtained by, e.g., Mullis et al. (2004), with a similar number of sources. This is because our sources are distributed in a much smaller volume than that sampled by the NEP survey and, by being on average less luminous, have an intrinsic higher space density resulting in a larger number of close source pairs.

In the linear theory of structure formation, the bias factor defines the relation between the ACF of large-scale structure tracers and the underlying overall matter distribution. In the case of X-ray selected AGNs, we can define the following relation: \( \xi_X(r, z) = b_X(r, z)^2 \xi_{dm}(r, z) \), where \( \xi_X \) and \( \xi_{dm} \) are the ACF of AGNs, DM, and the AGN bias factor, respectively.

In order to compute the bias factor of the AGNs in our whole sample, we used the prescription by Hopkins et al. (2007), and their host galaxies. By using the bolometric correction prescribed by Hopkins et al. (2007), we estimated from \( <L_X> \), \( <L_{BD}> \), and \( <L_B> \) (B-band luminosity). \( L_B \) is related to the black holes mass and the stellar mass of the host galaxy via scaling relations (Marconi & Hunt 2003). From \( <M_{BH}> \), we derived \( <L_{Ed}> \) and the Eddington rate \( \epsilon = <L_{Ed}>/<L_{Ed}> \) (see Table 2 for a summary). We point out that the estimates obtained above have several limitations which mostly arise from the uncertainties on scaling relations and from the broad range of luminosities sampled here. We therefore consider these values as estimate for the “average” local AGN population.

5. SUMMARY AND DISCUSSION

In this Letter, we report on the measurement of clustering of 199 AGNs in the local universe using the Swift-BAT all-sky survey sample. This result gives, for the first time, an unbiased picture of the z = 0 DMH–galaxy–AGN coexistence/evolution. We obtained a correlation length \( r_0 = 5.56^{+0.49}_{-0.43} \) Mpc h^{-1} and \( \gamma = 1.64^{+0.07}_{-0.09} \). We measured the ACF for Type I and Type II AGNs and found a significant difference in their correlation lengths. We have measured a marginally significant higher \( r_0 \) for high-luminosity AGNs than for the low-luminosity ones. We propose that the observed difference in Type I versus Type II AGNs is driven by the intrinsic higher \( <L_X> \) of Type I AGNs, as we show a marginal evidence of a correlation between \( r_0 \) and \( L_X \). We estimated the typical mass of the DMH hosting an AGN of the order \( \log(M_{DMH}) = 13.15^{+0.09}_{-0.13} \) h^{-1} M/M⊙. In Figures 3, we show the bias-redshift plane results from AGN and galaxy surveys (references in the figure). In the same plot, we show the expected evolution of different DMH masses. We compared only bias values of studies that rely on the real space correlation function \( \xi(r) \) (values of \( \sigma_8_{AGN,GAL} \) from Krumpe et al. 2010). This approach allows us to compare all different clustering studies on a common basis.

The majority of the X-ray surveys agree with a picture where AGNs are typically hosted in DM halos with mass of the order

\[ \rho_p(z) = \frac{\rho_{AGN}(L,z)}{\rho_{DMH}(M,z)} \tau_H(z) \]

at a given redshift.\(^9\) For the whole sample at \( z \sim 0 \), \( n_{DMH} \sim 6.7 \times 10^{-4} \) Mpc^{-3} (Hamana et al. 2002) and \( n_{AGN} \sim 3.4 \times 10^{-3} \) Mpc^{-3} (Sazonov et al. 2007) which leads to an estimate of \( \tau_{AGN}(z = 0) \sim 0.68 \) Gyr. To fully characterize our sample, we derived the average properties of the active BHs and their host galaxies. By using the bolometric correction prescribed by Hopkins et al. (2007), we estimated from \( <L_X> \), \( <L_{BD}> \), and \( <L_B> \) (B-band luminosity). \( L_B \) is related to the black holes mass and the stellar mass of the host galaxy via scaling relations (Marconi & Hunt 2003). From \( <M_{BH}> \), we derived \( <L_{Ed}> \) and the Eddington rate \( \epsilon = <L_{Ed}>/<L_{Ed}> \) (see Table 2 for a summary). We point out that the estimates obtained above have several limitations which mostly arise from the uncertainties on scaling relations and from the broad range of luminosities sampled here. We therefore consider these values as estimate for the “average” local AGN population.

\( a \) AGN bias factor.
\( b \) Mass of the typical dark matter halo hosting an AGN.
\( c \) AGN duty cycle in Gyr.
\( d \) Black hole mass.
\( e \) Eddington ratio.
\( f \) Stellar mass of the bulge.

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### Table 1

Summary of the Results

| Sample | \( <z> \) | \( <\log(L_X)> \) | \( r_0 \) (Mpc h^{-1}) | \( \gamma \) | \( \rho_p(z) \) (Mpc^{-3} h^{3} M⊙) |
|--------|----------|-----------------|-----------------|--------|------------------|
| All    | 199      | 0.045           | 43.2            | 5.56^{+0.49}_{-0.43} | 1.64^{+0.07}_{-0.08} | 5.55^{+0.1}_{-0.1} |
| Type I | 96       | 0.046           | 43.37           | 7.93^{+1.14}_{-1.09} | 2.1^{+0.20}_{-0.25} | 8.12^{+1.57}_{-1.00} |
| Type II| 103      | 0.024           | 42.87           | 4.72^{+0.60}_{-0.69} | 1.78^{+0.24}_{-0.19} | 4.96^{+0.20}_{-0.17} |
| HL     | 99       | 0.054           | 43.67           | 13.92^{+5.48}_{-6.59} | 1.41^{+0.15}_{-0.17} | 5.63^{+1.57}_{-2.57} |
| LL     | 100      | 0.023           | 42.55           | 3.37^{+0.51}_{-0.68} | 1.86^{+0.25}_{-0.17} | 3.56^{+0.15}_{-0.66} |

### Table 2

Bias Factor and Mass of the Dark Matter Halos Hosts of the AGNs in the Samples

| Sample | \( b_X^2 \) | \( M_{DMH}^{10^{12}} \) (M/M⊙) | \( r_{AGN} \) (Gyr) | \( log(M_{BH})^d \) | \( log(\epsilon)^e \) | \( M^f \) (10^{12}/M⊙) |
|--------|-----------|-------------------------------|-----------------|-----------------|-----------------|-----------------|
| All    | 1.21^{+0.06}_{-0.07} | 13.1^{+0.09}_{-0.13} | 0.68 | 8.51 | -1.96 | 18.2 |
| Type I | 2.01^{+0.15}_{-0.13} | 13.9^{+0.15}_{-0.21} | 4.99 | 8.79 | -2.02 | 31.6 |
| Type II| 1.08^{+0.26}_{-0.29} | 12.9^{+0.11}_{-0.38} | 1.32 | 7.96 | -1.85 | 63.8 |
| HL     | 2.28^{+0.96}_{-0.90} | 14.0^{+0.37}_{-0.70} | 3.91 | 9.28 | -2.12 | 80.5 |
| LL     | 0.80^{+0.06}_{-0.16} | 11.8^{+0.34}_{-0.57} | 0.24 | 7.43 | -1.68 | 2.28 |

Notes:

- \( a \) Number of sources in the Sample.
- \( b \) \( r_0 \) obtained by freezing \( y = 1.7 \) in the fit.
By merging the observational evidences and the model predictions, a plausible scenario for the history of local AGNs is the following.

1. Swift-BAT AGN switched on about 0.7 Gyr ago after a galaxy merger event.
2. They shine in an Eddington-limited regime for the first part of their lives where they gain most of their mass.
3. In the second phase of their lives (i.e., after 0.2–0.5 Gyr), they start to accrete with lower and lower efficiency. Their luminosity drops because of the decreased gas reservoirs.
4. At \( z \approx 0 \), they have grown to \( \sim 10^{10}–10^{10.5} M_\odot \) SMBHs, shining as moderately low-luminosity AGNs at low accretion rates.

We thank Gigi Guzzo, Roberto Gilli, Angela Bongiorno, and Simon White for the useful comments. Support from NASA NNX07AT02G, CONACyT 83564, PAPIIT IN110209 is acknowledged.

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\(^{10}\) HL and type I estimates may be wrong because of the relatively young age of \(10^{14} (M_\odot / h)\) DMH.