A rich bounty of AGN in the 9 deg\(^2\) Boötes survey: high-

\(z\) obscured AGN and large-scale structure

Ryan C. Hickox\(^1\), Christine Jones\(^1\), William R. Forman\(^1\), Stephen S. Murray\(^1\), Almus Kenter\(^1\), Mark Brodwin\(^2\), and the Chandra XBoötes, NOAO Deep Wide-Field Survey, Spitzer IRAC Shallow Survey, and AGES Teams

Abstract. We use observations from the 9 square degree multiwavelength survey in Boötes to identify hundreds of obscured active galactic nuclei (AGN) with high redshifts (\(z > 0.7\)), luminosities (\(L_{\text{bol}} > 10^{45}\) ergs s\(^{-1}\)), and moderate obscuring columns (\(N_{\text{H}} > 10^{22}\) cm\(^{-2}\)), and to measure the clustering properties of X-ray AGN at \(z > 1\). In the Boötes region, shallow (5 ks) Chandra X-ray observations have detected \(\sim 4,000\) X-ray sources, and the same region has been mapped with deep optical imaging and by Spitzer IRAC, which detects \(\sim 300,000\) point sources, of which \(\sim 30,000\) have detections in all four IRAC bands, for which we can select AGN on the basis of their mid-IR colors. With the MMT/Hectospec we have obtained modest resolution optical spectra for about half the X-ray sources (out to \(z > 3\)) and \(\sim 20,000\) galaxies (out to \(z = 0.7\)). With this multiwavelength data we select \(>400\) AGN per square degree (compared to 12 per square degree from SDSS). Among a sample of IRAC-selected AGN we identify 641 candidate obscured objects based on their \(R\) band and IRAC luminosities. We use X-ray stacking techniques to verify that they are obscured AGN and measure their absorbing column densities. We also measure the three-dimensional two-point correlation function for X-ray selected AGN.

1. The Boötes multiwavelength dataset

In studies of AGN, wide-field surveys are complementary to deep surveys such as the GOODS fields in that they explore the rare, bright end of the luminosity function and constrain spatial distributions over large angular scales. In the Boötes region, shallow (5 ks) Chandra X-ray observations have detected \(\sim 4,000\) X-ray sources, of which most are AGN, to a limiting 0.5–7 keV flux of about \(4 \times 10^{-15}\) ergs cm\(^{-2}\) s\(^{-1}\) (Murray et al. 2005; Kenter et al. 2005). The region has also been mapped by deep \(B_W, R,\) and \(I\) imaging with the NOAO Deep Wide-Field Survey (NDWFS, Jannuzi & Dey 1999), and by the Spitzer IRAC Shallow Survey, which detects \(\sim 300,000\) point sources, of which \(\sim 30,000\) have 5\(\sigma\) detections in all four IRAC bands, and for which AGN can be selected on the basis of their mid-IR colors (Eisenhardt et al. 2004). Using the MMT Hectospec multi-fiber spectrograph, the AGES survey has obtained modest resolution optical spectra for about half the X-ray sources out to \(z > 3\) and \(\sim 20,000\) galaxies.

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\(^1\)Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

\(^2\)Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
Figure 1. **Left:** $R$ band versus mid-IR luminosity for 1410 infrared-selected AGN from the Boötes field. The dashed line shows an empirical criterion selecting obscured (bottom) and unobscured (top) AGN. **Right:** Hardness ratio versus $z$ for the two types of IR-selected AGN. Gray lines show $HR$ for an intrinsic $\Gamma = 1.8$ and two values of $N_{\text{H}}$. The obscured objects have systematically harder X-ray spectra, corresponding to $N_{\text{H}} \sim 3 \times 10^{22} \text{cm}^{-2}$.

out to $z=0.7$ (Kochanek et al. 2006, in preparation). These optical, infrared, and X-ray techniques select >400 AGN per square degree.

Redshifts for objects are obtained spectroscopically using the AGES spectra, or using photometric redshift estimators based on the IRAC and optical photometry (Brodwin et al. 2006). Photo-$z$’s have uncertainties $\sigma_z = 0.06(1 + z)$ for galaxies at $z < 1$, and $\sigma_z = 0.12(1 + z)$ for optically bright AGN.

2. Identifying obscured AGN

In the standard picture of AGN emission, observations at X-ray, optical, and IR wavelengths correspond to different regions in the central engine. X-rays are emitted in the inner regions close to the black hole, the optical/UV continuum is emitting by the accretion disk, and optical broad and narrow lines are produced by illuminated gas surrounding the accretion disk. Infrared emission is produced by the reprocessing of UV and X-ray emission by surrounding dust.

Methods for detecting AGN on the basis of their optical and X-ray emission are well established. Recently, new techniques using IRAC have allowed the identification of AGN on the basis of their observed colors in the mid-infrared, where AGN tend to have a red power-law continuum that separates them from starburst galaxies in color-color space (e.g., Lacy et al. 2004; Stern et al. 2005). Because mid-IR emission is less affected by obscuration from dust and gas than the optical or soft X-rays, this technique allows the detection of obscured AGN that may be missed with other techniques (e.g., Alonso-Herrero et al. 2006; Martínez-Sansigre et al. 2006).

We identify obscured AGN from a color-color selected sample using observed optical and IR luminosities (Hickox et al. 2006). Fig. 1 shows the distribution in observed $\nu L_{\nu}$ in the $R$ band and IRAC bands for 1410 IRAC-selected AGN at $z > 0.7$. The luminosity distribution shows two clear populations: (1) objects in which $L_R$ increases with $L_{\text{IRAC}}$, and are associated with sources having optical broad-line AGN spectra, and (2) objects with roughly constant $L_R$ over two
orders of magnitude in $L_{\text{IRAC}}$. We classify the first population of 769 objects as unobscured AGN (IRAGN 1) and the second 641 objects as AGN for which the optical light is obscured (IRAGN 2), with a boundary between them of $\log L_R/L_{\text{IRAC}} = -0.4$.

We verify this simple selection of obscured AGN using (1) the Chandra X-ray observations, and (2) the observed optical colors and morphologies. Because the Chandra observations are shallow, most objects have no more than a few X-ray counts. Therefore, we perform stacking analyses to determine the average fluxes and spectra of the different subsets of objects. We find that the IRAGN 1s and IRAGN 2s have similar X-ray luminosities ($L_X \sim 10^{43} - 10^{44}$ ergs s$^{-1}$), but the IRAGN 2s have significantly harder X-ray spectra, shown by a larger value of the hardness ratio $HR = (H - S)/(H + S)$, where $H$ and $S$ are observed counts in the 0.5–2 and 2–7 keV bands, respectively (Fig. 1). Assuming a typical AGN power law X-ray spectrum with photon index $\Gamma = 1.8$, this indicates absorption by a neutral hydrogen column of $N_H \sim 3 \times 10^{22}$ cm$^{-2}$, which is typically in the range of “obscured” AGN in population models (e.g., Treister & Urry 2005).

The optical colors of the IRAGN 2s are also typical of normal galaxies rather than nuclear AGN emission, indicating that the nuclear optical light is obscured. Fig. 2 shows $B_W - R$ and $R - I$ color versus redshift for the two IRAGN types compared with quasar (Vanden Berk et al. 2001) and galaxy (Fioc & Rocca-Volmerange 1997) templates. The IRAGN 2s are redder than would be expected for an unobscured quasar. Also, the IRAGN 2s have extended morphologies, while the unobscured IRAGN 1s are dominated by point-like nuclear emission.
The X-ray and optical properties of the IRAGN 2 sample therefore are consistent with these 641 objects being a population of AGN with high luminosities ($L_{\text{bol}} > 10^{45}$ ergs s$^{-1}$) redshifts ($z > 0.7$), and moderate obscuration ($N_H > 10^{22}$ cm$^{-2}$). This one of the largest such samples identified to date, made possible by the wide field and extensive multiwavelength data in the Boötes region.

3. AGN clustering properties

The contiguous X-ray coverage in the Boötes field has allowed us to spectroscopically target, and obtain accurate redshifts, for a large number of AGN at $z > 0.7$, and so observe large-scale structure out to $z = 1$ and beyond. We have determined the three-dimensional two-point correlation function for the X-ray selected AGN, and find significant evidence for clustering (Fig. 3, Kenter et al. 2006, in preparation). The inferred clustering parameters are consistent with those found by the optically-selected 2dF Quasar survey (Croom et al. 2005).

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