FOSSIL HUNTING: CHANDRA ASSOCIATES LOCAL XBONGS WITH POOR GALAXY GROUPS
DARYL HAGGARD, ANCA CONSTANTIN, EWAN O’SULLIVAN, PAUL J. GREEN, SCOTT F. ANDERSON, DONG-WOO KIM

ABSTRACT
We present Chandra observations of eight candidate Optically Dull X-ray Bright Galaxies at low redshift (z ~ 0). Six of the eight appear to be extended in the X-ray, indicating the presence of hot intra-cluster (or intra-group) gas, and are thus candidate poor clusters, groups, or fossil groups.

1. INTRODUCTION
Why do some luminous X-ray sources (L_X \gtrsim 10^{42} \text{ erg s}^{-1}, rest-frame 2 – 8 keV) lack any detectable optical emission lines? Such high X-ray luminosities require power from accretion onto supermassive black holes, which typically produce copious UV photons to photoionize the line-emitting circumnuclear gas. Resolving this puzzle is crucial for understanding: (i) the AGN phenomenon and its cosmic evolution, and (ii) the completeness of optically selected samples.

While the first examples were discovered some 25 years ago (Elvis et al. 1981), there is still no consensus as to why XBONGs lack the optical signature of accretion activity. Several distinct phenomena are suspected, some bland, others exotic.

1) Dilation by the host galaxy starlight (e.g., Moran et al. 2002, Caccianiga et al. 2007) is certainly possible, particularly for higher-z sources in the Chandra deep fields and the XMM-Newton XBS surveys, where most of these sources have been found, because their optical spectra are obtained through relatively large projected apertures.

2) The absence of emission lines could be due to obscuration by either Compton-thick cold gas and dust covering almost 4\pi at the nuclear source (e.g., Comastri et al. 2002), or simply by extranuclear dust in the host galaxy (Rigby et al. 2006).

3) Radiatively Inefficient Accretion Flows (RIAFs). Yuan & Narayan (2004) describe how truncation of the standard Shakura-Sunyaev accretion disk at large inner radii leads to insufficient UV (“big blue bump”) photons to photoionize the line-emitting circumnuclear gas, while the infalling gas is nevertheless heated (by upscattering of the low-energy seed photons) to high enough temperatures to emit a hard X-ray power-law.

4) Variability Tidal disruption of a star may cause transient AGN phenomena that would be consistent with extreme variability events recorded in ROSAT observations (Komossa et al. 2004) or the luminous UV flare found with GALEX (e.g., Gezari et al. 2006).

5) Extended hot gas probably associated with galaxy clusters or groups, may have escaped detection in low signal-to-noise X-ray observations (e.g., Georgantopoulos & Georgakakis 2005) especially at high redshifts. Moreover, an unknown fraction of XBONGs could be “fossil groups.” These systems are optically dominated by a single giant elliptical (by definition, > 2 mag in R band difference between the 1st and 2nd brightest galaxies), and host extended X-ray emission with L_X > 10^{42} \text{ erg s}^{-1} (Jones et al. 2003). While these latter two possibilities seem likely, and would have important scientific impact, they have never been systematically investigated.

The contributions of these various possibilities remains ambiguous because investigations into the nature of these mysterious objects employ small samples, lack high quality optical spectra which permit reliable deconvolution of the emission-line spectrum from the host star-light, or have X-ray imaging at insufficient quality. To date, the largest z = 0.37 datasets of optically passive galaxies with L_X > 10^{42} \text{ erg s}^{-1}, and with both X-ray and rest-frame optical information, employ < 4 sources (e.g., Caccianiga et al. 2007). The few XBONGs that are analyzed in depth cover almost the whole range of possibilities invoked in explaining this phenomenon. Civano et al. (2007) illustrate the unfortunate “state of the art” of nearby XBONG studies, i.e., out of their four sources considered, two are interpreted as weak obscured sources with moderate amounts of gas and dust covering a large solid angle. One is associated with an X-ray extended source. For the last one, the spectral fitting does not permit a firm conclusion.

While XBONG detections at high z seem to be flourishing, their optical dullness is uncertain as there is no H\alpha information. High-quality X-ray observations are still needed to determine if the X-ray spectra of XBONGs are hard due to absorption or to a different accretion mode. However, exposures that would yield interesting new spectral constraints for the high-z examples remain prohibitive (\gtrsim 1 Msec). Our low-z sample offers better S/N, H\alpha coverage in all the optical spectra, and better spatial resolution to resolve and quantify possible extended X-ray emission. Host optical morphology is also more easily studied, with the unique advantage of SDSS high quality photo-z’s to characterize the local environment in every field. A well-selected local sample is by far the best hope for understanding these elusive AGN.

Here we present propose new ACIS-S X-ray observations of the cleanest and most homogeneously defined sample of X-ray Bright Optically Normal Galaxies (XBONGs). This program aims to constrain proposed models for XBONGs as optically obscured/diluted AGN, radiatively inefficient AGN with intermediate Eddington ratios, or galaxies dominated by (fossil) group/cluster emission.
2. SAMPLE SELECTION

All of the XBONGs detected so far have been hard X-ray selected objects for which optical follow-up spectroscopy revealed a surprising dearth of emission-line activity. The reverse approach, in which well characterized optically selected passive galaxies are found to be X-ray bright, will reveal the most reliable sample of XBONGs. In a bold attempt to investigate the soft X-ray properties of the SDSS galaxies, Parejko et al. (2008) revealed an impressively large fraction of passive galaxies with a high likelihood of being counterparts of RASS Faint Source Catalog (Voges et al. 2000) sources and X-ray luminosities $\gtrsim 10^{42}$ erg s$^{-1}$.

For our low $z$ "passive galaxy" sample, we require no detectable emission in H$\alpha$, H$\beta$, or [OIII]$\lambda$5007. For SDSS spectra, the high S/N, wide wavelength coverage (including H$\alpha$) and the fact that the emission and absorption optical features are identified and measured after the spectra have been corrected for the host galaxy stellar light, makes this sample of passive galaxies the cleanest ever. Our simulations of the RASS-SDSS source-separation use RASS positional errors plus a linear random component, carefully removing a large range of possible X-ray contaminants (spectroscopic and photometric quasars, bright stars, other emission-line systems) to make the matching process the most secure yet. No other sample of XBONG candidates is as well characterized: the SDSS observations provide a wealth of properties, from direct measures of their absolute brightness, color, and morphology, to good (indirect) estimates of their stellar and black hole masses, and mean age of their stellar populations (MPA/JHU catalogs, Brinchmann et al. 2004; http://www.mpa-garching.mpg.de/SDSS/).

The "dullness" of these objects is remarkable in imaging as well as spectroscopy. Optical surface brightness decomposition based on a non-linear optimization of two-component fits considering a deVaucouleur galaxy model and a point source (SDSS specific PSF; pipeline described in Hyde et al. 2008), reveal for our sample high host fractions, with no optical evidence for an AGN component. A cross-match with the Faint Images of the Radio Sky at Twenty centimeters survey (FIRST, Becker et al. 1995) catalog of sources with flux densities exceeding 1 mJy at 1.4 GHz reveals that none of these XBONGs candidates are radio-loud. Thus, if present in these sources, the AGN are indeed peculiar.

A possible association with groups or clusters is not yet excluded, and constitutes an important part of this project. Most RASS sources cannot reliably be distinguished as extended unless their extent exceeds $\sim 1'$ (Bohringer et al. 2000). Nevertheless, a likelihood-extent analysis can exclude 97% of point sources above an extent of 25". Using an extent likelihood $> 7$ and source extent $> 25''$ as in Bohringer et al. (2000), none of the objects included in our sample are considered extended in X-rays.

To eliminate objects that may not be true XBONGs, we have excluded the systems possibly associated with Abell clusters and the MaxBCG (SDSS-based) clusters of Koester et al. (2007). With these criteria, at least in photo-$z$ space, our RASS-XBONG candidates are no more clustered than non-RASS passive galaxies (Figure 1). This suggests that the detected X-ray emission is very likely to come from the galaxy itself (i.e., an AGN) rather than from hot gas in an associated group or cluster.

Chandra is needed to confirm and "resolve" XBONGs at low $z$. With its high throughput and excellent spatial resolution, the ACIS detector on Chandra is the tool to employ in discriminating among the above listed possibilities. We propose to observe a sample of 8 strong XBONG candidates. We aim to detect 500 counts for each for accurate determinations of the absorption and power-law indices and a precise measure of any spatial extent.

We will be able to disentangle cases of intrinsically hard X-ray spectra, compatible with the RIAF model for accretion (which fits observations of the XBONG P3; Yuan & Narayan, 2004), from cases where the spectral hardness originates in absorption. If these galaxies show weak absorption, but intrinsically hard X-ray spectra, they would be the strongest evidence yet that the optical/UV-faint accretion mode is not an exception but an important late phase in the AGN evolution process. Intrinsic (absorption corrected) $L_X$ will be used in conjunction with black hole masses (derived from stellar velocity dispersions) to estimate their corresponding Eddington ratios, and thus provide the first quantitative constraints on this mode/phase of accretion.

Our analysis of the 16 spectroscopically passive SDSS galaxies serendipitously detected in 323 fields from the ChaMP Multiwavelength Project (ChaMP; Green et al. 2004) reveals that none X-ray luminous enough to be classified as XBONGs (Constantin et al. 2009). Those 16 passive galaxies have relatively soft spectra and $L_X < 10^{42}$ erg s$^{-1}$ (Figure 2), which clearly demonstrates the scarcity of bona fide XBONGs, and the importance of identifying them from the wide RASS/SDSS fields. We note that the ChaMP study provides a unique Chandra comparison sample at lower $L_X$ to the proposed XBONGs.

Only Chandra’s sensitivity and spatial resolution will enable us to address with the new observations all five possibilities listed above: (1) The issue of point-source vs. extended X-ray source nature of XBONGs will be clearly settled, and if our targets are all X-ray point sources, small projected-aperture (HST) spectroscopy should confirm the buried (spectroscopically diluted) AGN. (2) If absorption is found to be the main cause of XBONGs’ dearth of optical emission lines, we will provide essential constraints on the distribution of absorption columns in these objects. (3) If the observations confirm the RIAF accretion mode, the range of XBONG host properties, black hole masses and accretion rates, will place...
XBONGs in the context of other AGN, and reveal novel signals of accretion black holes in the absence of ongoing star-formation. (4) We will test the transient phase (e.g., tidal disruption) hypothesis by comparing the Chandra and RASS fluxes, taking both bandpass and spectral shape into account. (5) If Chandra confirms that the X-ray emission comes from extended hot ICM, the sample will provide an important addition to the sparse data currently available for such systems at moderate redshift; only ∼20 such groups have been identified at 0 < z < 0.6 (Fassnacht et al. 2007; Jeltema et al. 2006; Mulchaey et al. 2006; Willis et al. 2005), and only half of them have measured gas temperatures, a key property in that it is closely correlated with mass.

The possible detection of fossil groups will be of particular interest as their properties can be used as a test of structure formation models; such systems are expected to form at very early epochs and evolve passively, but despite their predicted space density comparable to poor clusters (Jones et al. 2003), only a handful have been identified at low redshift. The luminosity and temperature of any identified groups can be compared to the $L_X - T_X$ and $L_X - \sigma$ relations for groups in the local Universe to search for evolution in these properties, and the morphology of the groups could provide information on the fraction of these system undergoing or recovering from recent mergers. No other X-ray telescope can offer such information, particularly regarding the morphology. Note that for testing the other alternatives proposed to explain the XBONG phenomenon Chandra is again the unique tool capable to extract the necessary spectral neutral component.

### 3. OBSERVATIONS AND DATA REDUCTION

#### 3.1. Target Selection

Both extended and compact emission are important in investigating the nature of XBONGs at low $z$. We thus need to consider the Chandra field of view (FoV) in 2 competing ways: (1) If all the X-ray emission is from a nuclear point source, subarrays might be needed to avoid pileup, and (2) If we need to encompass and characterize extended emission, a large FoV is necessary. To fit a ∼ 1 Mpc extended source while retaining sufficient chip area for background estimation, we use a simple cut in redshift, 0.2 < z < 0.37. For $z \approx 0.3$, 1 Mpc = 5 arcmin, which is conveniently covered with one full chip, and thus well matched to the secondary goal of constraining possible (fossil) cluster emission. There are 8 XBONG candidates, with $z$ falling within this range, $L_X \gtrsim 10^{42}$ erg s$^{-1}$, and which are not associated with known extended sources, as described in the previous section. The maximum RASS-SDSS source separation in our sample is 20$''$, with matching likelihoods from 78% to 90%.

[DH: Need to search for matches in 2MASS!]

#### 3.2. Chandra Observations

Determining the absorption and measuring the power law index requires only a few hundred counts. If the counts are extended (e.g., cluster/group emission), a comparison with Khosroshahi et al. (2007) suggests that 500 counts are necessary to fit a spatial $\beta$-model to an accuracy of $\sigma_\beta = 0.05$, and temperatures to ∼ 0.1 keV, adequate to determine whether these objects fall (to 1$\sigma$) on the group $L_X - T_X$ relation. The image will show whether the hot ICM contours are relaxed, which would rule out recent merger activity, as their optical spectra already appear to do. If the counts are from an AGN, our experience fitting ACIS-S imaging spectra for hundreds of SDSS AGN in the ChaMP (Green et al. 2008) suggests typical 90% confidence-level constraints of ±0.3 in power-law slope $\Gamma$ and ±1 × 10$^{20}$cm$^{-2}$ for intrinsic absorption, even in the presence of extended cluster or non-nuclear point source emission (10-50% of total counts; Green et al. 2002).

To derive the exposure times necessary to achieve ∼ 500 counts, we use PIMMS. To convert ROSAT to ACIS-S counts, we assume $\Gamma = 1.9$ and the Galactic $N_H$ appropriate for each galaxy. For 500 counts total per XBONG, the total exposure for these 8 XBONGs is 86 ksec. Note that pile-up could be a problem for one of these bright sources. With the sample cut described above, the brightest source has RASS-cps = 0.66. If all counts are from an AGN, then with no subarray, we get 13% pileup for an unabsorbed AGN spectrum. But if there is intrinsic $N_H = 10^{22}$, we predict 38% pileup on ACIS-S. We thus choose to use a custom subarray (startrow = 128, for 768 rows) which yields 6.3 arcmin FoV, enough to encompass 1 Mpc, but keeping pileup below 5% for all sources.

[DH: Describe XPIPE data reduction and point source extraction.]

### 4. ANALYSIS

Here we describe the optical and X-ray observations of the eight XBONG candidates selected for this Chandra observing program in detail.

#### 4.1. Multiwavelength Matching

Besides our 8 matches (by selection) to SDSS and RASS Paul finds:

- one match to NVSS within 5$''$ (J204744-061847 = 311.9367/-06.313)
- 3 matches to GALEX within 5$''$ (J085441.7+305754 = 133.7137/30.8891; J1200+4834 = 180.1929/48.5771; J204744-061847 = 311.9367/-06.313)
- No matches to 2XMMi within 5as.
- Possibly 1 XMM Slew Survey match within (just over) 5$''$ (J085441.7+305754 = 133.7137/30.8891)
FIG. 3.— Smoothed thumbnail images for the 8 Chandra XBONG candidates. The Chandra source IDs (OBSID) are marked in each panel (from left to right): top row 11668, 11667, 11666; middle row 11665, 11664, 11663; bottom row 11662, 11661.

TABLE 1
OPTICAL PROPERTIES

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Note. — Velocity dispersion from Schlegel; D4000\(_n\) from Balogh et al. 1999, ApJ, 527, 54... \(^a\) Multiwavelength matches within 5" from other archives: Galaxy Evolution Explorer (GALEX), XMM Slew Survey (XMMSS), NRAO VLA Sky Survey (NVSS).

TABLE 2
X-RAY PROPERTIES

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<th>Name (SDSS J)</th>
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<th>L(_X) (erg s(^{-1}))</th>
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Note. — X-ray fluxes and luminosities are quoted in the 0.5-8.0 keV band. Luminosity estimates assume the SDSS redshift (see Table 1). \(^a\) f\(_X\), (L\(_X\)) is the measured point source flux (luminosity) or upper limit if no point source was detected within XXX of the optical source position. \(^b\) [DH]: Give brief description of matching probability. \(^c\) [DH]: Note whether sources are extended/diffuse, variable?, RIAF?
systems would be more interesting to me, but if they turn out to be clusters and the X-ray source). Their might be some clusters, but if they are unidentified systems, looking at surface density of groups, hardness maps might give some indication, and surface brightness fits, to allow extrapolation from the aperture to a total gas luminosity. Group-scale spectroscopic targeting algorithms and is identified as a z = 0.2747 Galaxy (Fig. 5). The spectrum confirms its classification as a [massive] elliptical [need to calculate $D_{\text{SDSS}}$, mass, etc.]. According to the MPA/JHU catalog ([OIII]) is weakly detected ($f_{\text{OIII}} = 0.677864 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$, EW([OIII]) = 0.033031), but others of the narrow lines are not detected (e.g., MPA/JHU catalog reports a negative H$\beta$ flux, but EW(H$\beta$) = 0.574866). Hence placement on the BPT diagram is not possible/straightforward and the source was targeted as a candidate XBONG.

4.3. Spectral and Radial Profile Fits

Notes from Ewan:

Since the objects are diffuse, the most important issues for me would be to determine temperature, luminosity, their general temperature structure, and to get some idea of the associated galaxy population. Spectral fits will provide a mean temperature, which will determine whether they are clusters or groups and give an estimate of the virial radius. I would suggest doing X-ray surface brightness fits, to allow extrapolation from the aperture to a total gas luminosity. Group-scale systems would be more interesting to me, but if they turn out to be clusters this might have implications for cluster surveys based on RASS.

I don’t know whether there are enough counts in any of the objects to address temperature structure (i.e., the presence of a central cool core) via spectral fitting. If they are groups, hardness maps might give some indication, and surface brightness fits will also help. Cool core status will give an idea of how relaxed these systems are, and whether they have recently merged - the images suggest several are cool cores.

Looking back at the proposal I see that the targets were selected to exclude known cluster members. I’m not sure if there have been any SDSS group/cluster surveys published in the last couple of years that might be used to check this. Just looking at the Tago et al (2010) group catalogue, I see that they have an outer limit of $z=0.2$, I think because the completeness of the redshift survey drops off beyond that point. If these are unidentified systems, looking at surface density of galaxies on the sky around each target might be worthwhile. I would expect to see some increase even for fossil groups.

4.3.1. SDSS J1200+4834 (OBSID 11664)

SDSS J1200+4834 (RA, Dec = 180.1929, 48.5771) is our brightest SDSS optical counterpart and the Chandra source with the brightest/most distinctive X-ray emission (Figure 3, middle row, central image). [DH: It is also one of the GALEX sources mentioned above.] In SDSS DR7 imaging SDSS J1200+4834 appears to be an early-type galaxy, with several nearby photometric sources (Fig. 4). This source was also selected via the SDSS TARGET_ROSAT_E, TARGET_ROSAT_D, TARGET_GALAXY, and TARGET_GALAXY_RED spectrophotometric targeting algorithms and is identified as $z = 0.2747$ Galaxy (Fig. 5). The spectrum confirms its classification as a [massive] elliptical [need to calculate $D_{\text{SDSS}}$, mass, etc.]. According to the MPA/JHU catalog ([OIII]) is weakly detected ($f_{\text{OIII}} = 0.677864 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$, EW([OIII]) = 0.033031), but others of the narrow lines are not detected (e.g., MPA/JHU catalog reports a negative H$\beta$ flux, but EW(H$\beta$) = 0.574866). Hence placement on the BPT diagram is not possible/straightforward and the source was targeted as a candidate XBONG.

A series of views of the Chandra imaging for this target are shown in Figure 6 (the GTI-corrected exposure time is 13992.7 sec; see also Fig. 10). The top left panel shows the full ACIS-S3 chip (ccdid=7; the custom subarray of 768 rows is visible to the trained eye) with wavdetect sources from the XPIPE pipeline overplotted (blue circles). The extended X-ray source in the bottom center is roughly coincident with SDSS J1200+4834 and is clearly visible in the smoothed, zoomed image (source 7, top right panel). The XPIPE X-ray source position is RA, Dec = 180.1924, 48.5772 (x, y = 4119.2500, 4126.6875).

The point source flux (from XPIPE) for source 7 is $f_{0.3-8.0} = 3.368 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ from within a 3 $''$ circular radius. At a redshift of $z = 0.2747$, this converts to an projected radius of 12.5 kpc and an X-ray luminosity of $L_X[0.3-8keV] = 7.9346 \times 10^{42}$ erg s$^{-1}$ (using $H_0 = 70$ and a luminosity distance of $D_L = 1403.2$ Mpc). The source’s ROSAT luminosity is $L_X[0.5-8keV] = 4.266 \times 10^{42}$ erg s$^{-1}$. [DH: I’ll need to review how the ROSAT flux/luminosity was extracted; since the source is extended I may need re-extract the ROSAT flux within a appropriate projected radius to compare with the calculations below.]

To improve the source centroiding for the extended X-ray emission, we fit a 2-D Gaussian profile (with constant background) to the data within a radius of 80 pixels (39.36 $''$), which corresponds to a projected radius of 165 kpc at the redshift of SDSS J1200+4834. [DH: This isn’t standard and should probably be changed to $r_{500}$ or $r_{200}$... but maybe it doesn’t matter for centroiding?] The best-value position for this fit is RA, Dec = 180.1932, 48.5771 ($x,y = 4115.85, 4125.8$); we adopt this as the source position for the remainder of our analysis. A visualization of the 2D Gaussian fit is shown in Figure 7, the left panel shows a plot of the fit in physical units and the right panel shows the raw data, the best-fit model, and the residuals (from left-to-right, top-to-bottom). The FWHM of the fit is 27.4+/−1.7 pixels (13.5+/−0.8 $''$), which corresponds to a physical scale of 56.5+/−3.3 kpc at $z = 0.2747$. In the bottom two panels of Figure 6 we zoom in further to the scale of the SDSS images shown in Fig. 4 (100 $''$×100 $''$) and show smoothed and smoothed visualizations of the X-ray emission region. The smoothing is performed with a 2D Gaussian kernel, embedded in a 5-sigma.
array, with a normalization equal to 1, and a sigma of 10 pixels along each axis.

An X-ray spectrum for OBS11664 source 7 is extracted at the 2D Gaussian profile position and shown in Figure 8. The spectrum is extracted with the specextract script provided with CIAO 4.2. A MEKAL model (appropriate for emission from hot diffuse gas) plus fixed galactic absorption is fit to the spectrum. We assume the hot X-ray gas is associated with the galaxy SDSS J1200+4834 and thus fix the redshift for the fit at $z = 0.2747$. The parameters for the fit are $nH = 0.0256 \times 10^{22}$ atoms cm$^{-2}$ (fixed), $kT = 3.47$ keV, Abundance = 0.617421 solar, and normalization = 0.000566738 (red line, Fig. 8). From this fit we assign an intragroup gas temperature of $kT = 3.47$ keV.

The X-ray model energy flux (within $\sim 60''$ or 250 kpc) is $f_X[0.3-8keV] = 4.3033 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. At a redshift of $z = 0.2747$, this converts to an X-ray luminosity of $L_X[0.3-8keV] = 1.014 \times 10^{44}$ erg s$^{-1}$.

We fit a radial profile to the extended X-ray emission in order to determine its surface brightness flux and calculate a hardness ratio. We extract source counts from 30 equally-spaced annuli (minimum radius = 6 pixels, maximum radius = 100 pixels), located around (but excluding) the central source. Background counts are also extracted from an annulus placed just outside this configuration (inner radius = 100, outer radius = 125). Since XPIPE did not detect additional point sources in the region, we do not worry about contaminating point sources. In Figure 9 we plot the midpoint surface brightness for each annulus as a function of position. We also fit the standard Beta Model to this surface brightness profile. This is a hydrostatic isothermal model that assumes that both the hot gas and the galaxies are in hydrostatic equilibrium and isothermal (Jones & Forman 1984, with a King profile [King 1962]), and can be converted into a gas mass and density (in theory):

$$S(R) = S_0(1 + (R/r_c)^2)^{-3\beta+0.5}$$

where $r_c$ is the core radius of the gas distribution. The parameter $\beta$ is the ratio of specific energy in galaxies to the specific energy in the hot gas:

$$\beta = \mu m_p \sigma^2 / kT_{\text{gas}}$$

where $\mu$ is the mean molecular weight, $m_p$ is the mass of the proton, $\sigma$ is the one-dimensional velocity dispersion, and $T_{\text{gas}}$ is the temperature of the intragroup medium. Our best fit for these parameters quantities are: $S_0 = 0.519863$ counts/pixel$^2$, $r_c = 13.09$ pixels ($= 6.44'' = 26.97$ kpc), and $\beta = 0.592452$. Hence at $R = 100$ pixels ($= 49.2'' = 206.22$ kpc, i.e. very nearly $r(0)$), $S(R) = 0.002822$ counts/pixel$^2$. [DH: Need to convert to physical units.] From our spectral fit, we know that $kT$...
Fig. 6.—Four images of OBS11664, chip ACIS-S3 (ccd=7) at various zooms and smoothing. (Top Left) The full ACIS-S3 chip containing the X-ray counterpart to SDSS J1200+4834. The custom subarray of 768 rows used throughout this Chandra program is visible. The point source positions determined by the XPIPE pipeline are marked as blue circles. The counterpart (source 7) to SDSS J1200+4834 is at the bottom middle of the chip and is visibly extended in the X-ray. (Top Right) A zoomed, smoothed image roughly centered on X-ray source 7. (Bottom Left) The X-ray data centered on X-ray source 7 and scaled to mimic the zoom for Fig. 4 (100′′ × 100′′). (Bottom Right) A smoothed version of the bottom left panel; the smoothing is performed with a 2D Gaussian kernel, embedded in a 5-sigma array, with a normalization equal to 1, and a sigma of 10 pixels along each axis.

\[ DH: \text{Need to calculate a hardness ratio too.} \]

5. DISCUSSION

[DH: Include Jeltema or similar figure here with our data included. (Could use plot data extraction tool that Kenza recently discovered.)]

6. SUMMARY AND CONCLUSIONS
**Fig. 7.** (Left) A 2-D Gaussian profile (with constant background) fit to source 7 within a radius of 80 pixels (39.36 ″), which corresponds to a projected radius of 165 kpc at the redshift of SDSS J1200+4834. This profile is primarily used to improve the source position centroiding for the extended emission. (Right) From top left to bottom left: the data within the extraction region, the 2D Gaussian profile fit, and the residuals of the fit.

**Fig. 8.** (Top) X-ray spectrum for OBS11664 source 7. The fit is for a MEKAL (Mewe-Kaastra-Liedahl) plus fixed galactic absorption model appropriate for emission from hot diffuse gas. (Bottom) The residuals for the fit.
FIG. 9.— A radial profile in physical units (i.e. counts/pixel$^2$ vs. pixels) fit with a 1D Beta Model (red line) in 30 consecutive radii from the source position. (Details of the fit can be found in the text.)

FIG. 10.— A histogram of background count rate from ACIS-S3 (ccd id = 7) during the observation of SDSS J1200+4834 from XPIPE. I assume this indicates that there are no background flares to worry about in this observation, but please correct me if this is not correct!