DETECTION OF X-RAY EMISSION FROM GRAVITATIONALLY LENSED SUBMILLIMETER SOURCES IN THE FIELD OF ABELL 370

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ABSTRACT

We report the detection by Chandra of SMM J02399−0134 and SMM J02399−0136, two distant (z = 1.06 and z = 2.81, respectively) submillimeter sources gravitationally magnified by the galaxy cluster Abell 370. These are high-significance (>7σ) X-ray detections of the high-redshift submillimeter source population. The X-ray positions are coincident with the optical positions to within 1″. The X-ray spectra, while of low signal-to-noise ratio, are quite hard. Absorbed power-law models with fixed photon indices of Γ = 2.0 imply local absorbing columns greater than 2 × 10^{23} cm^{-2} and unabsorbed luminosities greater than 10^{44} ergs s^{-1} in both sources. These results imply that nuclear activity is responsible for the bulk of the luminosity in SMM J02399−0134 and for at least 20% of the luminosity of SMM J02399−0136, consistent with previous optical observations. We also place an upper limit on the X-ray flux of a third submillimeter source, SMM J02400−0134. Considered together with previously published Chandra upper limits on the X-ray flux from submillimeter sources, our results imply that 20±10% of submillimeter sources exhibit X-ray emission from active galactic nuclei (with 90% confidence), consistent with expectations of their contribution to the diffuse X-ray background.

Subject headings: galaxies: active — galaxies: clusters: individual (Abell 370) — submillimeter — X-rays: galaxies

1. INTRODUCTION

Deep surveys with the Submillimeter Common-User Bolometer Array (SCUBA; Holland et al. 1999) in the fields of rich clusters (Smail et al. 1998) and in blank fields (e.g., Hughes et al. 1998; Barger, Cowie, & Sanders 1999a; Eales et al. 1999) have revealed a large population of luminous, star-forming galaxies at high redshift. This population produces a substantial fraction of the diffuse infrared background (Fixsen et al. 1998). While the contribution of active galactic nuclei (AGNs) to the total luminosity of these distant SCUBA sources is uncertain, this population accounts for at least as much star formation as has been inferred from UV/optical counts (Dwek et al. 1998; Blain et al. 1999). Besides its significance for the star formation history of the universe, a subset of the submillimeter source population may also host the obscured AGN thought to be responsible for the diffuse X-ray background (Almaini, Lawrence, & Boyle 1999, hereafter ALB99; Hasinger 2000; Fabian et al. 2000). X-ray background models (ALB99; Gunn & Shanks 1999) and optical spectroscopy of submillimeter sources (Barger et al. 1999b, hereafter B99) both suggest that ∼5%−20% of SCUBA sources should contain an AGN.

Deep X-ray observations with the Chandra X-Ray Observatory can test this connection directly. Here we report high-significance X-ray detections of bright submillimeter sources at high redshift and the first X-ray spectral constraints on this population. The three submillimeter sources that we discuss, SMM J02399−0136, SMM J02399−0134, and SMM J02400−0134, are gravitationally magnified by Abell 370 and are detected at a greater than 4σ significance by SCUBA (Smail, Ivison, & Blain 1997; B99). We detect the first two of these, which are hereafter designated CX1 and CX2, respectively. Both X-ray–detected sources were previously identified with high-redshift (z = 2.81 and z = 1.06, respectively) star-forming galaxies containing AGNs (Ivison et al. 1998, hereafter I98; Soucail et al. 1999, hereafter S99). We place an upper limit on the X-ray flux from the third source, which has no optical counterpart to a limiting magnitude of I ∼ 26 (Smail et al. 1998; B99).

2. OBSERVATIONS

Chandra observed Abell 370 with the AXAF CCD Imaging Spectrometer (ACIS) S3 detector (G. P. Garmire et al. 2000, in preparation) in 1999 October for 93 ks. The net useful exposure time, excluding periods of high background and bad aspect, is 66.6 ks. Events in ASCA grades 1, 5, and 7 were excluded, and, unless otherwise noted, our analysis is restricted to the 0.3−7 keV spectral range.

2.1. Source Detection and Astrometry

We ran the Chandra X-ray Center’s WAVDETECT wavelet source detection program on an 8′4 × 8′4 field containing the cluster. We used wavelet kernel scales of 1″−8″ and set the threshold detection significance parameter to 10^{-7}. Two of the 34 sources detected are positionally coincident with the submillimeter sources described above to within 2″.

In Table 1, we list the X-ray positions and compare them with the best available optical positions (source L1 of I98 for CX1 and of S99 for CX2) for the identified submillimeter sources. Formal random errors in the X-ray positions are of order 0″2 in each axis. Systematic errors of ∼1″5 may affect the Chandra aspect solution currently available for this observation. We compared the positions of other compact sources detected in the Chandra image with various optical catalogs and found four stellar objects in the Automatic Plate Measuring (APM) catalog with positions within 3″ of sources detected in the ACIS-S3 field. The mean coordinate differences between the Chandra and APM frames derived from these objects are listed in Table 1. The standard deviation of each of these mean

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differences is 0\arcsec.5, and the external accuracy of the APM astrometry is claimed to be \(\sim 0\arcsec.5\).

We adopt the mean Chandra-APM offset as the Chandra boresight error and find that the Chandra and optical positions for both sources agree to within 1\arcsec. The X-ray source positions (from other ACIS detectors) for the four objects in the USNO catalog thus corrected have a mean radial error of less than 1\arcsec.1. We note that the 3 mm radio position of CX1 (Frayer et al. 1998) agrees with both the optical and X-ray positions to within 1\arcsec. We also note that 14 X-ray sources at least as bright as CX1 are detected in the Abell 370 field; the probability of any of these detections by the Galaxy (fixed at cm; Stark et al. 20) is consistent with zero, within wide limits, for both sources. In the case of CX2, this model systematically over-predicts the data at both low and high energies, suggesting that additional absorption is required. The fit is better if both \(N_{\text{H}}\) and \(\Gamma\) are varied, but \(\Gamma\) is very poorly constrained. In the case of CX1, an \(F\)-test shows that the addition of local absorption does not produce a statistically significant improvement in the fit. For both sources, the indeterminacy in \(\Gamma\) is accompanied by a corresponding uncertainty in the absorbing column and in the intrinsic luminosity of the source.

Faced with this ambiguity, we fix the photon number index in our fits. The X-ray spectra of low-redshift AGNs generally exhibit (unabsorbed) continuum slopes in a restricted range (1.5 \(\leq \Gamma \leq 2.5\); e.g., Nandra et al. 1997; Turner et al. 1997).
Here we consider models with $1.5 \leq \Gamma \leq 2.0$. Any reflected component that is present is likely to be much harder and, if the obscuring column is sufficiently high, will dominate the observed emission, at least at lower energies.

Results of fits are presented in Table 2, where values for fixed $\Gamma = 1.5$ and $\Gamma = 2.0$ are separated by slashes and the 90% confidence envelope for these two cases is given in parentheses. To allow an interpretation of the X-ray flux either as directly transmitted (through an absorbing column) or as reflected emission, we quote both the “unabsorbed” and the “observed” 2–10 keV luminosity in the source rest frame. All tabulated luminosities have been corrected for the estimated gravitational magnification of 2.5 and assuming $q_s = 0$.

### Table 2

| Source | $N_{\text{H}1}^{a}$ (× 10$^{21}$ cm$^{-2}$) | $L_{\text{X, observed}}^{b}$ (× 10$^{44}$ $h_{54}$ ergs s$^{-1}$) | $L_{\text{X, unabsorbed}}^{b}$ (× 10$^{44}$ $h_{54}$ ergs s$^{-1}$) |
|--------|-----------------------------------|-----------------------------------|-----------------------------------|
| CX1    | 9/13 (5, 23)                      | 0.31/0.33 (0.12, 0.62)            | 3.0/6.4 (1.7, 8.8)                |
| CX2    | 2.1/2.7 (1.6, 3.5)                | 0.43/0.45 (0.40, 0.56)            | 1.0/1.4 (0.80, 1.8)               |

$^{a}$ Equivalent hydrogen column density at source.

$^{b}$ Luminosity in the 2–10 keV band in the source frame, corrected for gravitational magnification of 2.5 and assuming $q_s = 0$.

3. Discussion

From the positional coincidences discussed above, we may reasonably identify the Chandra and submillimeter sources. Here we discuss the role of the AGN in the bolometric luminosity of these sources and consider the implications of our results for the expected connection between the X-ray and submillimeter backgrounds.

3.1. The AGN Contribution to Bolometric Luminosity

The role of AGNs in the energetics of ultraluminous infrared galaxies remains an open question, particularly in the case of the objects thought to comprise the high-redshift submillimeter source population. In the following discussion, we adopt a gravitational magnification of 2.5 for both sources. The uncertainty in this value is no more than a factor of 2 in the case of CX1 and about ±10% in the case of CX2 (Kneib et al. 1993; IWA98; S99).

SMM J02399–0136 (CX1).—IWA98 presented comprehensive optical and infrared data that determined the redshift and that showed emission from a narrow-line, dust-obscured AGN. They report detection by the Infrared Space Observatory (ISO) at 15 μm but were unable to determine the relative importance of star formation and the AGN in producing the enormous bolometric luminosity of this object ($L_{\text{bol}} \sim 5 \times 10^{45}$ $h_{54}^{-1}$ $L_{\odot}$, assuming $q_s = 0$). Frayer et al. (1998) detected CO line emission in CX1, implying a large mass of molecular gas ($10^9 M_{\odot}$) and a relatively small ratio of far-infrared (FIR) to CO luminosity, indicating that star formation is important in this source. They conclude from the relatively low FIR-to-4.85 GHz flux ratio (50% $\pm$ 25% of the infrared luminosity may be powered by the AGN).

We find that the ratio of X-ray to bolometric luminosity for this source exceeds 1.5% for $\Gamma > 1.5$. Although this limit is rather low for radio-quiet quasars (Elvis et al. 1994), we note that at least two luminous type 2 AGNs, IRAS 23060+0505 (Brandt et al. 1997) and IRAS 20460+1925 (Ogasaka et al. 1997), have comparable or lower values of $L_{\text{X}}/L_{\text{bol}}$. Adopting the median bolometric correction $L_{\text{bol}}(1–10 \text{ keV})/L_{\text{bol}} = 0.05$ from Elvis et al. (1994), we find that $L_{\text{AGN}} = 9 \times 10^{45}$ ergs s$^{-1}$, about 40% of the FIR luminosity. Between 20% and 80% of the luminosity of CX1 is attributable to the obscured AGN if $1.5 \leq \Gamma \leq 2.0$.

The large column density ($N_{\text{H1}} > 10^{24}$ cm$^{-2}$ if $\Gamma = 2.0$) inferred for CX1 suggests that the obscuring material may be Compton-thick, in which case we must interpret the X-ray emission as predominantly reflected (rather than obscured) radiation from the central source. From the “observed” luminosity in Table 2, it follows that if the X-ray emission is due to the reflection from cold gas with an albedo of 0.022 (Iwasa, Fabian, & Matt 1997), then the nucleus in CX1 is of a quasar luminosity.

We can independently estimate the importance of the AGN in CX1 by comparing its submillimeter–to–X-ray flux ratio with that of the ultraluminous infrared galaxy NGC 6240, in which a highly obscured, powerful AGN dominates the bolometric luminosity (Vignati et al. 1999). Following Fabian et al. (2000), we characterize this ratio as an equivalent energy index $\alpha$, defined so that the spectral flux density $F_\nu \propto \nu^{-\alpha'}$. Taking $F_\nu$ at 850 μm and 2 keV from Table 1, we find that $\alpha = 1.30 \pm 0.03$. This value is less than that expected of NGC 6240 (observed at $z = 2.8$) by about a factor of 2 (corresponding to $\Delta \alpha \sim 0.05$; see Fig. 2). This might mean either that the fraction of scattered radiation is lower or that the AGN is relatively less luminous in CX1 than in NGC 6240.

SMM J02399–0134 (CX2).—S99 identified the ring galaxy LRG J0239–0134 with SMM J02399–0134, measured its redshift, reconstructed its intrinsic shape, and noted that the ring feature is indicative of interaction-induced star formation. The optical spectrum and the ISO mid-IR colors led S99 to identify the source as a Seyfert 1 galaxy. From a Keck Low-Resolution Spectrograph (LRG) spectrum, Hornschemeier et al. (2000) both modified as described in the text) and the ISO data (diamonds with error bars). Alternative curves for NGC 6240 with less internal absorption ($N_{\text{H1}} = 5 \times 10^{23} h_{54}^{-1}$) or a smaller scattered flux fraction ($f_s = 0.01$) are also shown (adapted from Fabian et al. 2000 and Hornschemeier et al. 2000).
The X-ray luminosity and spectrum of this source confirm the presence of a powerful, obscured AGN. Applying a bolometric correction to the unabsorbed X-ray luminosity yields \( L_{\text{bol}} \sim 3 \times 10^{35} \text{ ergs s}^{-1} \), which dominates the luminosity in the submillimeter (B99) and the mid-IR (S99). For CX2, \( \alpha = 1.12 \), which is quite comparable to the value expected if NGC 6240 were observed at \( z = 1.06 \), allowing for the relatively smaller observed absorbing column in CX2 (Fabian et al. 2000; see Fig. 2).

3.2. The X-Ray/Submillimeter Connection

Two other searches with Chandra for X-ray emission from submillimeter sources have yielded only upper limits or detections that are marginal in the submillimeter or X-ray bands. Fabian et al. (2000) report upper limits for six SCUBA sources in two cluster fields, with typical flux upper limits (uncorrected for gravitational magnification) in the deeper field of \((4.5) \times 10^{-15} \text{ ergs s}^{-1} \text{ cm}^{-2} (2-7 \text{ keV}) \). Hornschemeier et al. (2000) report upper limits for 10 SCUBA sources from a very deep (166 ks) Chandra image containing the Hubble Deep Field (HDF), with typical upper limits of \( 0.8 \times 10^{-15} \text{ ergs s}^{-1} \text{ cm}^{-2} (2-8 \text{ keV}) \). Given the cluster X-ray emission, we estimate our 99% confidence detection threshold for sources near the center of A370 to be about \( 1.5 \times 10^{-15} \text{ ergs s}^{-1} \text{ cm}^{-2} \) in the 1.5-7 keV band for sources with the spectrum (\( \Gamma = 2.0 \), and no intrinsic absorption) assumed by both groups.

We must estimate the fraction of submillimeter sources that have detectable AGNs using a sample that has been observed to an explicit limiting submillimeter–to–X-ray flux ratio (i.e., to a particular limiting value of \( \alpha \), as defined above). We adopt our lower limit for SMM J02400–0134, viz., \( \alpha > 1.29 \) (determined from the hard-band flux). While none of the limits on \( \alpha \) from Fabian et al. (2000) and only one of the limits from Hornschemeier et al. (2000) are this high, we note that both groups compute flux by assuming \( \Gamma = 2.0 \) and no absorption at the source. We observe spectra much harder than this assumed model. Accordingly, we recompute the previously published flux limits using a flat (\( \Gamma = 0 \), unabsorbed) spectrum and find that the (hard-band) X-ray flux density limits drop by about a factor of 2. After making this adjustment, we find that seven of the HDF limits are sufficiently stringent to have detected a source with \( \alpha < 1.29 \). In this sample, two of 10 submillimeter sources (20%±6%, where errors give the central 90% confidence interval for a binomial distribution) have detectable X-ray emission. Fisher’s exact probability test (Petrucci, Nandra, & Chen 1999, p. 682) shows that the probability of finding the observed detection rates, given the identical detection efficiency in Abell 370 and the HDF is modest (6.7%) but not implausible.

After this Letter was submitted, Severgnini et al. (2000) reported that one of the nine sources detected with SCUBA in the Hawaii SA13 field by Barger et al. (1999a) was also detected in the Chandra survey of SA13 by Mushotzky et al. (2000). The detected source has \( \alpha = 1.06 \), based on the hard-band flux, and the lower limits on \( \alpha \) for the other sources span 1.1 < \( \alpha < 1.2 \). Thus, the SA13 data are not sensitive to as low an X-ray–to–submillimeter flux ratio as are ours. Nevertheless, if we pool these sources together with all the other Chandra observations of submillimeter sources discussed above, without regard to sensitivity and including marginal detections, we find that seven of the 32 submillimeter sources have Chandra counterparts.

The X-ray–detected fractions in both samples are quite consistent with the predictions of ALB99, who model the IR emission of the AGNs that produce the diffuse X-ray background and find that 10%–20% of sources detected at 850 \( \mu \)m should be AGNs. Similarly, the “conservative” models of Gunn & Shanks (1999) predict an AGN fraction of 5%–15%, which is also consistent with our results.

In summary, we have detected powerful, hard X-ray sources in two luminous, high-redshift submillimeter sources. Both of these objects were previously known from optical spectra to contain AGNs, and in both, the AGNs are probably responsible for a substantial fraction of the bolometric luminosity, although star formation is clearly important in SMM J02399–0136. The proportion of submillimeter sources detected by Chandra to date is consistent with models that synthesize the cosmic X-ray background from obscured AGNs at high redshift.

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