AN ENSHROUDED ACTIVE GALACTIC NUCLEUS IN THE MERGING STARBURST SYSTEM ARP 299 REVEALED BY BeppoSAX

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ABSTRACT

Using a long (=150 ks) broadband (0.1–40 keV) BeppoSAX observation of the merging starburst system Arp 299 (=IC 694 + NGC 3690), we found the first unambiguous evidence of the presence of a deeply buried \((N_H \approx 2.5 \times 10^{24} \text{ cm}^{-2})\) active galactic nucleus (AGN) having an intrinsic luminosity of \(L_{0.5-100\text{keV}} \approx 1.9 \times 10^{43}\) ergs s\(^{-1}\). The X-ray spectral properties of this AGN are discussed in detail, as well as the thermal component detected at soft X-ray energies, which, most likely, is associated with the starburst.

Subject headings: galaxies: active — galaxies: individual (IC 694, NGC 3690) — galaxies: nuclei — galaxies: starburst — X-rays: galaxies

I. INTRODUCTION

Studies of active objects at IR and X-ray wavelengths indicate that star formation and active galactic nucleus (AGN) activity may be related (Fadda et al. 2002). The triggering mechanism for both phenomena could be the interaction or the merging of gas-rich galaxies. This generates fast compression of the available gas in the inner galactic regions, causing both the onset of a major starburst and the fueling of a central black hole that raises the AGN activity (see Combes 2001 for a recent review). These two processes may proceed with different timescales, and once initiated, they probably have different lifetimes. Therefore, a detailed study of the relative importance of starburst and AGN activity in the nearest (and brightest) objects may have profound impact on the understanding of the evolution and the fate of the gas in the interaction process, on the modeling of the cosmological evolution of both AGNs and starburst objects (e.g., Franceschini, Braitot, & Fadda 2002), and on the evaluation of the contribution of these sources to the energy density of the universe (e.g., Fabian et al. 1998).

The concomitant AGN and starburst activity is expected to happen in a high-density medium \((N_H \gtrsim 10^{23}–10^{24} \text{ cm}^{-2})\), characterized by high dust extinction of the UV-optical flux and strong photoelectric absorption of the soft X-rays (e.g., Fabian et al. 1998). Therefore, the study of these active phases in galaxies becomes very difficult. Specific examples are NGC 6240 and NGC 4945. Both objects have been classified as LINER and/or starburst galaxies on the basis of optical (Veilleux et al. 1995) and mid-/far-IR (Genzel et al. 1998) spectroscopy. For both objects, however, the BeppoSAX Phoswich Detector System (PDS) observations at \(E > 10\) keV have clearly revealed the presence of a deeply buried AGN \((N_H \approx \text{few} \times 10^{23}\) cm\(^{-2}\)) with a quasi-stellar object–like (QSO-like) intrinsic luminosity in the case of NGC 6240 \(L_{0.5-100\text{keV}} \sim 6 \times 10^{44}\) ergs s\(^{-1}\); Vignati et al. (1999) and a Seyfert-like luminosity in the case of NGC 4945 \(L_{0.5-100\text{keV}} \approx 7 \times 10^{43}\) ergs s\(^{-1}\); Guainazzi et al. (2000). These two examples clearly show that optical and mid-/far-IR spectroscopy may not be sufficient to disentangle starburst activity from AGN activity, which is actually best probed in the hard \((E > 6\) keV) in order to sample also the Fe K\(\alpha\) line X-ray energy band.

To shed light on the starburst-AGN connection and its occurrence, we have started a systematic and objective investigation in hard \((E > 6\) keV) X-rays of a flux-limited sample of IRAS galaxies. The sample consists of 28 galaxies selected from the IRAS Cataloged Galaxies and Quasars as having \(f_{\text{IR}, 100\mu m} > 50\) Jy or \(f_{\text{25\mu m}} > 10\) Jy. We stress here that no other selection criteria (e.g., established presence of an AGN, luminosities, IR colors, etc.) have been applied to the sample definition.

In this Letter, we present and discuss BeppoSAX observations of Arp 299, a merging system (composed of IC 694 and NGC 3690 but simply quoted as NGC 3690 in the IRAS catalog) located at \(D = 44\) Mpc \((z = 0.011); Heckman et al. 1999, hereafter H99), spectroscopically classified as starbursting from optical (Coziol et al. 1998) and mid-/far-IR (Laurent et al. 2000) observations. Its total far-IR (FIR: 43–123 \(\mu m\)) luminosity, \(2.86 \times 10^{11} L_\odot\) (following the recipe in Helou et al. 1988 and using the IRAS Faint Source Catalog fluxes; Moshir et al. 1990), dominates the bolometric luminosity. As shown in this Letter, the BeppoSAX observations unveil a strongly absorbed \((N_H \approx 2.5 \times 10^{24}\) cm\(^{-2}\)) AGN with an intrinsic (unabsorbed) luminosity of \(L_{0.5-100\text{keV}} \approx 1.9 \times 10^{43}\) ergs s\(^{-1}\); this is the first unambiguous evidence of the presence of an AGN in the interacting system Arp 299. For a detailed description of the system and for a summary of previous multiwavelength observations, see Zezas, Georganopoulos, & Ward (1998, hereafter ZGW98), H99, Hibbard & Yun (1999), Alonso-Herrero et al. (2000), and Charmandaris, Stacey, & Gull (2002). In this Letter, we assume \(H_0 = 75\) km s\(^{-1}\) Mpc\(^{-1}\) and \(q_0 = 0.5\).

2. OBSERVATIONS AND DATA REDUCTION

Arp 299 was observed by BeppoSAX (Boella et al. 1997) on 2001 December 14–18 for about 150 ks. In this Letter, we use data collected from the Low Energy Concentrator Spectrometer (LECS), the Medium Energy Concentrator Spectrometer (MECS), and the PDS.

1 See http://irsa.ipac.caltech.edu.
The cleaned and linearized data produced by the BeppoSAX Scientific Data Center (SDC)\(^8\) have been analyzed using standard software packages (XSELECT version 1.4, FTOOLS version 4.2, and XSPEC version 11.0). At the best spatial resolution of the BeppoSAX instruments (~2\(\prime\)), Arp 299 is not resolved; no significant source flux variation was detected over the whole observing period. In the PDS field of view (~60\(\prime\) radius), there are no known and bright (2–10 keV) X-ray sources except Arp 299. In the ROSAT All Sky Survey catalog, we found only two QSOs within 60\(\prime\) from Arp 299; given their lower flux and off-axis angle, we can exclude them as sources of contamination in the PDS energy range.

To maximize statistics and signal-to-noise ratio (S/N), the LECS and MECS source counts were extracted from a circular region of 4\(\prime\) radius; background counts were extracted from high Galactic latitude “blank” fields (provided by the BeppoSAX SDC). The PDS spectrum extracted with the standard pipeline (with the rise-time correction applied) was provided directly by the BeppoSAX SDC; the simultaneously measured off-source background was used. In our analysis, we took into account only data in the 0.1–4 keV and 1.8–10 keV energy ranges for the LECS and MECS, respectively (as suggested in the BeppoSAX Cookbook).\(^9\) Spectral channels corresponding to energies 10–40 keV have been used for the PDS data. LECS and MECS (PDS) source counts have been rebinned to have a S/N > 3 (S/N > 2) in each energy bin. Standard calibration files released by the BeppoSAX SDC (1997 September version) have been used. The LECS to MECS and PDS to MECS normalization factors were allowed to vary in the ranges proposed by the BeppoSAX Cookbook. Net exposure times (count rates) are 63,830 s (0.0087 ± 0.0004 counts s\(^{-1}\)) for the LECS, 177,050 s (0.0124 ± 0.0003 counts s\(^{-1}\)) for the MECS, and 75,490 s (0.0852 ± 0.0187 counts s\(^{-1}\)) for the PDS.

3. SPECTRAL ANALYSIS

Single-component models\(^10\) do not provide an adequate description of the broadband (0.1–40 keV) spectrum of Arp 299. A single-temperature thermal model or a single unabsorbed power-law model are both rejected at a confidence level greater than 99.9%. Figure 1 shows the ratio of BeppoSAX LECS, MECS, and PDS data to the best-fit unabsorbed power-law model (\(\Gamma \approx 1.9\)). A bump at ~0.8 keV, a line-like feature at ~6.4 keV, and a big bump in the PDS energy range (10–40 keV) are clearly evident. The residuals suggest the presence of a soft thermal component around 0.8 keV, which is a characteristic signature in all known starburst galaxy X-ray spectra (e.g., Dahlem, Weaver, & Heckman 1998). The simultaneous occurrence of a strong line-like structure at ~6.4 keV and of a big bump in the PDS energy range is the distinctive spectral signature of an obscured AGN (Matt et al. 2000).

Given these features, we have performed a broadband fit that includes (1) a soft thermal model, (2) an unabsorbed power-law with photon index \(\Gamma\), (3) a Gaussian emission line at ~6.4 keV, and (4) an absorbed power-law having the same photon index \(\Gamma\). The combination of the spectral components 2 and 4 is usually called a “leaky-absorber” model, in which the absorbed power law (accounting here for the PDS energy range) represents the “first-order” AGN continuum emerging after transmission through an obscuring cold medium (torus? starburst-related dust?). The unabsorbed power law (accounting here for the MECS energy range) represents the primary AGN spectrum scattered into the line of sight by a warm highly ionized gas located outside the absorbing medium. Furthermore, the residuals (not reported here) still show a clear line-like excess at ~3.5 keV, which has been modeled with a Gaussian emission line. The results of this best-fit model\(^12\) (\(\chi^2/\text{dof} = 104.2/118\)) are reported in Table 1 and shown in Figure 2.

4. DISCUSSION

4.1. The AGN Component

The BeppoSAX data provide unambiguous evidence of the presence of AGN emission from Arp 299, with an intrinsic (i.e., unabsorbed) luminosity of \(L_{\text{0.5–100 keV}} \approx 1.9 \times 10^{44} \text{ergs s}^{-1}\).

The intrinsic power-law photon index (\(\Gamma = 1.79^{+0.05}_{-0.03}\)) is very similar to that usually observed in Seyfert 1 galaxies (Nandra et al. 1997). The primary continuum is highly absorbed (\(N_{\text{HI}} = 2.5 \times 10^{24} \text{cm}^{-2}\), with a 99% confidence level lower limit of ~1.76 \times 10^{24} \text{cm}^{-2}\) and can escape from the absorber only at energies above 10 keV; this indicates that a deeply buried “Compton-thick AGN” lies in the interacting system Arp 299. The scattered flux fraction (given here as the ratio of the normalizations of the unabsorbed to absorbed power-law components) implied from the fits is 5% ± 3%, similar to that usually found in Seyfert 2 galaxies (e.g., Turner et al. 1997).

At the spectral resolution of the BeppoSAX MECS, the Gaussian line at ~6.4 keV is unresolved, with a rest-frame energy position of 6.42 ± 0.13 keV and an observed equivalent width (EW) of 636 ± 270 eV. This value is significantly larger than that observed in Seyfert 1 galaxies (EW = 230 ± 60 eV; Nandra et al. 1997) but is similar to that measured in Seyfert 2 galaxies.

\(^8\) See http://www.asdc.asi.it/bepposax.
\(^9\) F. Fiore, M. Guainazzi, & P. Grandi 1999, Cookbook for BeppoSAX NFI Spectral Analysis (ftp://sax.sdc.asi.it/pub/sax/doc/software_docs/saxabc_v1.2.ps.gz).
\(^10\) All models discussed here have been filtered through a foreground Galactic absorption of \(N_{\text{H G}} = 9.92 \times 10^{21} \text{cm}^{-2}\) (Dickey & Lockman 1990). The thermal component(s) have been modeled with the MEKAL model. All quoted errors are at the 90% confidence level for 1 parameter of interest (\(\Delta x^2 = 2.71\)).
\(^11\) Given that the intrinsic \(N_{\text{HI}}\) is expected to be high (\(\sim 10^{24} \text{cm}^{-2}\)), we have used the PLCABS model (Yaqoob 1997), which describes the X-ray transmission correctly taking into account Compton scattering.
\(^12\) A simpler model described by a power law plus a thermal component and a Gaussian line at ~6.4 keV is rejected by the data at a confidence level greater than 99% (\(\chi^2/\text{dof} = 162.1/122\)).

![Fig. 1.—Ratio of the unabsorbed power-law model to the BeppoSAX LECS (open triangles), MECS (filled circles), and PDS (open squares) data. The PDS to MECS normalization factor is constrained to vary within the range indicated by the BeppoSAX Cookbook.](image-url)
TABLE 1

RESULTS OF THE SPECTRAL FIT (LECS+MECS+PDS): MEKAL THERMAL COMPONENT + ABSORBED AND SCATTERED POWER LAW + NARROW GAUSSIAN LINES ($\chi^2$/idof = 104.2/118) AND UNABSORBED X-RAY LUMINOSITIES

| Component | Model         | $kT$ (keV)/$kT_e$ (keV) | Norm. | $N_H/EW$ (eV) | Luminosity (ergs s$^{-1}$) |
|-----------|---------------|--------------------------|-------|--------------|-----------------------------|
| SB        | MEKAL$^a$     | 0.86$^{+0.20}_{-0.29}$   | 10.29$^{+5.03}_{-4.63}$ | ... | 1.12 $\times 10^{44}$ | 7.41 $\times 10^{44}$ | 5.36 $\times 10^{44}$ | 0.5–2 keV |
| AGN       | Absorbed power law | 1.79$^{+0.05}_{-0.05}$ | 590$^{+420}_{-420}$ | 2.52$^{+1.30}_{-0.36}$ | ... | 3.09 $\times 10^{44}$ | 4.93 $\times 10^{44}$ | 1.06 $\times 10^{44}$ | 2–10 keV |
|           | Unabsorbed power law | 1.79$^{+0.05}_{-0.05}$ | 26.93$^{+1.00}_{-0.00}$ | 3.09 | ... | ... | ... | ... | 10–100 keV |
| Lines (rest frame)$^b$ | 3.38$^{+0.26}_{-0.13}$ | 0.39$^{+0.03}_{-0.03}$ | 125$^{+38}_{-38}$ | ... | ... | ... | ... | ... |
|           |               | 6.42$^{+0.33}_{-0.33}$ | 0.68$^{+0.29}_{-0.29}$ | 636$^{+236}_{-236}$ | ... | ... | ... | ... |

Note.—Errors are quoted at the 90% confidence level for 1 parameter of interest ($\chi^2 = 2.71$). The LECS to MECS and PDS to MECS normalization factors (0.7 and 0.95, respectively) are consistent with the known differences in the absolute calibration of the instruments. The total observed fluxes of Arp 299 are 8.16 $\times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ (0.5–2 keV), 1.13 $\times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ (2–10 keV), and 3.23 $\times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ (10–100 keV).

$^a$ The metallicity of the thermal component was fixed to the solar one.

$^b$ In units of $10^{-19}$ (4πD$^2$)$^N_H$ for $N_H$ at 1 keV, where D is the distance of the source in centimeters, $N_H$ is the electron and H density in units of cm$^{-3}$, and V is the volume filled by the X-ray-emitting gas in cm$^3$.

$^c$ The two-power-law photon indexes have been fitted together.

$^d$ In units of 10$^{-7}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV.

$^e$ Column density of neutral hydrogen (in units of 10$^{22}$ cm$^{-2}$) in addition to $N_H$/G$_{disc}$ = 9.92 $\times 10^{20}$ cm$^{-2}$.

$^f$ The lines are unresolved at the spectral resolution of the BeppoSAX MECS.

$^g$ In units of 10$^{-7}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at the energy of the line.

(e.g., Bassani et al. 1999). The measured position is not consistent with He-like (6.7 keV) or H-like (6.96 keV) Fe, as expected if the line were produced inside the warm highly ionized gas that scatters the primary AGN spectrum. However, it is consistent with the low-ionization Fe-Kα line from cold material. This in turn leads to two possibilities: the line could be produced by a reflected and/or a transmitted component. The first possibility, however, is unlikely, since a significant reflection component cannot be easily accommodated within the BeppoSAX data (using the PEXRAV model, the 90% upper limit on the reflection fraction is 0.07). The second possibility involves the production of the cold Fe-Kα line by transmission through the same absorbing medium that affects the primary AGN continuum: indeed, the EW measured with respect to the transmitted component, ~7 keV, is consistent (within the errors on the intrinsic $N_H$) with what is expected from transmission (see, e.g., Leahy & Creighton 1993), making this possibility highly plausible. We note here that the absorbing medium in composite starburst-AGN galaxies, such as Arp 299, is not univocally associated with the putative absorbing torus, but the nuclear starburst itself could be a significant source of absorption (Fabian et al. 1998; Levenson, Weaver, & Heckman 2001). The measured EW (with respect to the transmitted component) for the Arp 299 line is a factor of ~3–4 above the prediction from the model in Ghisellini, Haardt, & Matt (1994) obtained using a simple toroidal geometry, which is a strong hint toward assuming that the above argument applies.

Finally, the unresolved Gaussian line at 3.38$^{+0.16}_{-0.13}$ keV (EW = 125 eV) is consistent with the Ar xviii Kα line. This line, which originates in the hot scattering medium itself (e.g., Netzer, Turner, & George 1998), has been observed also in the Compton-thick Seyfert 2 galaxy Circinus (EW ~ 60 eV; Sambruna et al. 2001). Based on the flux ratio of the Ar xviii Kα line to the Fe He-like line (which should be produced inside the same hot scattering medium) observed in Circinus, in Arp 299 we would expect an Fe He-like line with EW ~ 400 eV, a value consistent (within a factor of 2) with the derived 90% upper limit.

4.2. The Starburst Component

The best-fit soft X-ray thermal component gives $kT \approx 0.86$ keV. This value is consistent, within the errors, with that previously obtained by ZGW98 and H99 using the ROSAT Position Sensitive Proportional Counter (PSPC) plus ASCA data. It is also similar to that usually found in other well-studied starburst galaxies (e.g., Dahlem et al. 1998). This thermal emission likely originates from the interaction between hot low-density galactic winds and cold high-density interstellar matter (ISM; see H99).

Starburst galaxies are also characterized by a hard 2–10 keV spectral component interpreted as being either thermal with $kT \sim 5–10$ keV or nonthermal with $\Gamma \sim 1.5–2$ (e.g., Dahlem et al. 1998). Such a hard component is likely to be the integrated emission of X-ray binaries and can be modeled by means of a cutoff power law, $f(E) \propto E^{-p} e^{-E/E_c}$ (CPL model; see Persic & Rephaeli 2002).

In order to check to what extent the 2–10 keV emission from Arp 299 can be related to the starburst, in our model we have replaced the scattered AGN component (labeled as component 2 in § 3) with (1) a thermal component or (2) the absorbed CPL model under the hypothesis that the main contribution is due to X-ray binaries. Both alternatives are statistically viable, with (1) the thermal model with $kT = 6.58 _{-1.15}^{+1.74}$ keV or the unabsorbed CPL model with $\Gamma = 1.65 \pm 0.15$ ($kT$ fixed at 8 keV). In both cases, the spectral parameters of the soft X-ray component and of the absorbed AGN component remain consistent (within the errors) with those reported in Table 1. Since the inferred 2–10 keV luminosity of both the thermal and the CPL components is $\sim 2 \times 10^{44}$ ergs s$^{-1}$ (reasonable for a bright FIR galaxy such as Arp 299), we cannot rule out that at least part of the observed 2–10 keV X-ray luminosity is due to the X-ray binaries directly associated with the starburst (which may also contribute to the observed Fe-Kα emission). This conclusion was reached by ZGW98 and H99 using ASCA data.

13 It should be recalled that Fe-Kα emission is also typical of high-mass X-ray binaries (HMXBs) spectra (White, Swank, & Holt 1985). However, its EW, either observed directly in HMXBs (typically EW ~ 0.3 keV; see White et al. 1983) or inferred for galaxies with X-ray emission dominated by HMXBs (Persic & Rephaeli 2002), is inconsistent with the large value observed here (if the emission must be completely accounted for by HMXBs).

14 If this is the case, then the AGN scattered flux fraction reported in § 4.1, 5% ± 3%, should be considered as an upper limit.
In a BeppoSAX observation of the merging starburst system Arp 299, the 0.1–40 keV data coverage clearly reveals, for the first time in this system, the presence of a deeply buried ($N_H \approx 2.5 \times 10^{24} \text{ cm}^{-2}$) AGN with an intrinsic (i.e., unabsorbed) luminosity of $L_{0.1-100 \text{ keV}} \approx 1.9 \times 10^{45} \text{ erg s}^{-1}$. This AGN component was missed in previous multiwavelength observations. Assuming a Galactic standard value of $E_{\text{bol}}/N_H = 1.7 \times 10^{-22} \text{ mag cm}^2$ (Bohlin, Savage, & Drake 1978) and the measured $N_H$ value, we argue that the AGN is completely absorbed in the optical and IR band ($A_V > 1000 \text{ mag}$).

The intrinsic AGN’s X-ray luminosity is a factor of ~50 less than $L_{\text{FIR}} (\sim 10^{45} \text{ ergs s}^{-1})$. Thus, the total FIR luminosity of the system cannot be entirely associated with the AGN, even assuming an AGN UV luminosity a factor of ~10 greater than the X-ray luminosity (as observed in QSOs; e.g., Elvis et al. 1994). This suggests that the bulk FIR emission may be due to the starburst, in agreement with the results obtained by Laurent et al. (2000) using 5–16 μm ISOCAM data. This conclusion may also be supported by the fact that the ratio of the soft X-ray thermal emission (likely associated with the starburst) to the FIR emission ($\sim 10^{-4}$ in the case of Arp 299) is similar to other “bona fide” starburst galaxies such as M82 ($\sim 6 \times 10^{-5}$) and NGC 253 (7 × $10^{-4}$).

A question unsolved at the present stage is the location of the AGN inside the interacting system Arp 299. At the spatial resolution of the BeppoSAX instruments, we are collecting photons from Arp 299 ($= IC694 + NGC 5690$) as well as from the nearby galaxies Arp 296 and MCG +10-17-2a. It is safe to exclude the last two as the origin of the hard X-ray emission, since they are very weak sources in both the radio and the IR, and they were not detected in soft X-rays by ZGW98. On the other hand, both IC 694 and NGC 3690 could be the host of the AGN. We have recently retrieved the public Chandra and XMM-Newton data for this system. From a preliminary analysis, a strong line at ~6.4 keV is clearly present in NGC 3690 and maybe also in IC 694, suggesting the possible presence of two AGNs. The results of this analysis, which will also include an estimate of the binaries’ contribution to the 2–10 keV emission and a detailed comparison of the X-ray emission with that at other wavelengths, will be reported in a forthcoming paper.

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**Fig. 2.—Data fitted with a MEKAL thermal component, the leaky-absorber continuum, and two narrow Gaussian lines (see Table 1). (a) LECS (open triangles), MECS (filled circles), and PDS (open squares) folded spectra and data, (b) ratio of the data to the best-fit model, and (c) the unfolded model. Panel (c) insert: Confidence contours (68%, 90%, and 99% confidence level for two interesting parameters) for the power-law photon index and the absorbing column density.**

However, the ASCA statistics and energy coverage were insufficient to clearly detect the 6.4 keV Fe-Kα emission line and to reveal the high-energy bump. The new broadband BeppoSAX data instead clearly require the presence of an absorbed AGN component.

We have directly verified that the archival ASCA data are consistent with the best-fit spectrum reported in Table 1 and are not deep enough to clearly detect the 6.4 keV Fe-Kα emission line.
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