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FAR-INFRARED CHARACTERIZATION OF AN ULTRALUMINOUS STARBURST ASSOCIATED WITH A MASSIVELY ACCRETING BLACK HOLE AT $z = 1.15$

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ABSTRACT

As part of the All-Wavelength Extended Groth Strip International Survey (AEGIS), we describe the panchromatic characterization of an X-ray–luminous active galactic nucleus (AGN) in a merging galaxy at $z = 1.15$. This object is detected at infrared (8, 24, 70, and 160 μm), submillimeter (850 μm), and radio wavelengths, from which we derive a bolometric luminosity $L_{\rm bol} \sim 9 \times 10^{12}\ L_\odot$. We find that the AGN clearly dominates the hot dust emission below 40 μm but its total energetic power inferred from the hard X-rays is substantially less than the bolometric output of the system. About 50% of the infrared luminosity is indeed produced by a cold dust component that probably originates from enshrouded star formation in the host galaxy. In the context of a coeval growth of stellar bulges and massive black holes, this source might represent a "transition" object, sharing properties with both quasars and luminous starbursts. Study of such composite galaxies will help address how the star formation and disk-accretion phenomena may have regulated each other at high redshift and how this coordination may have participated in the buildup of the relationship observed locally between the masses of black holes and stellar spheroids.

Subject headings: cosmology: observations — galaxies: high-redshift — infrared: galaxies

Online material: color figures

1. INTRODUCTION

Galaxies with a bolometric luminosity exceeding $10^{12}\ L_\odot$ are often powered by a combination of massive star formation and accretion of material around active nuclei (e.g., Genzel et al. 1998). Early in cosmic history, the connection between these two phenomena may have led to a coeval growth of supermassive black holes (SMBHs) and stellar spheroids (e.g., Page et al. 2001) and could thus be the foundation of the correlation observed between the masses of these two components in the local universe (e.g., Gebhardt et al. 2000). However, the implication of such a coevolution in the more general context of the stellar mass built-up history (e.g., Dickinson et al. 2003) and SMBH formation (e.g., Barger et al. 2005) has not been fully addressed. Understanding the importance of this "coordinated" activity of starbursts and AGNs requires properly deconvolving their respective contributions *within individual objects*, a challenging task particularly for distant sources.

Because of the complexity of the AGN and starburst spectral energy distributions (SEDs), this decomposition can best be achieved by combining data from wave bands that offer distinctive spectral features to characterize these phenomena. For instance, active nuclei are strong emitters at high energy, and they are usually associated with a continuum of hot dust peaking in the mid-infrared (IR). Luminous starbursts, on the other hand, are characterized by a colder dust component and emit the bulk of their luminosity in the far-IR. To illustrate how the coexistence of these two processes at high redshift could be studied using larger samples, we present a panchromatic analysis of a luminous AGN referenced as CXO GWS J141741.9+522823 (hereafter CXO J1417) by Nandra et al. (2005). It is embedded in an ultraluminous infrared galaxy (ULIRG) at $z = 1.15$, and its detection across the full electromagnetic spectrum allows us to constrain the level of star formation also present in this source. We assume a ΛCDM cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\lambda = 0.7$.

2. THE DATA

CXO J1417 is a bright X-ray source also known in the literature as CFRS 14.1157 or CUDSS 14.13. It is associated with a very red galaxy ($I - K_{\rm AB} \sim 2.6$: Webb et al. 2003; see also Wilson et al. 2007) detected in the mid-IR (Flores et al. 1999; Higdon et al. 2004; Barmby et al. 2006; Ashby et al. 2006), submillimeter (Eales et al. 2000; Webb et al. 2003), and radio (Fomalont et al. 1991; Chapman et al. 2005). High-resolution images obtained with *HST* (Davis et al. 2007; Lotz et al. 2007) reveal several components presumably interacting with each other (see Fig. 1). The brightest is dominated by a point source located at R.A. = $14^{\rm h}17^{\rm m}41.89^{\rm s}$, decl. = $52°28'23.65''$ (J2000.0, δR.A. $\sim \delta$decl. $\sim 0.07''$), coinciding precisely with the position of the X-ray detection (Miyaji et al. 2004).

At this location, there is also a bright and pointlike object detected at 70 and 160 μm. In spite of the large beam used for the data at

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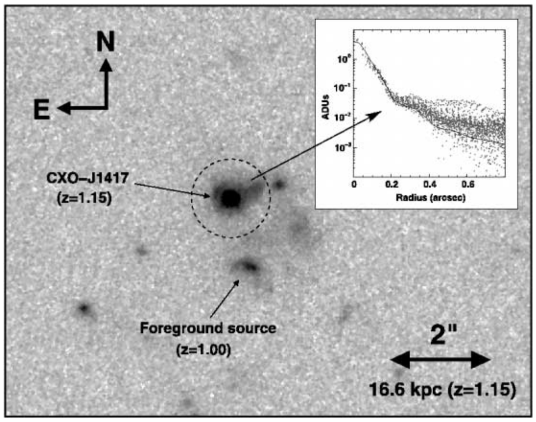

FIG. 1.—F814W ACS image of CXO J1417 ($z = 1.15$) with the 95% error location of the X-ray source indicated by the dashed-line circle (Miyaji et al. 2004). The inset illustrates the profile of this component in the F814W image. The comparison with the PSF (*solid line*) reveals that the central core is not resolved by *HST*. The object lying 1.4″ to the south is a foreground galaxy at $z = 1.00$. [*See the electronic edition of the Journal for a color version of this figure*.]

long wavelengths,[18] the fact that the mid-IR counterpart of CXO J1417 is 2 orders of magnitude brighter than any other galaxies detected at 24 μm in this area strongly suggests that this far-IR emission is also associated with the X-ray source. Its fluxes in the MIPS 24/70/160 μm bands were measured via point-spread function (PSF) fitting. They are reported in Table 1, which also summarizes the full multiwavelength photometry of the object (see Davis et al. 2007 for a description of our data set). Optical and near-IR fluxes were measured within a 1″ radius aperture centered at the position of CXO J1417. With the exception of the *GALEX* data, where we believe that the emission is contaminated by a blue galaxy lying 1.4″ to the south, our flux measurements refer exclusively to the component hosting the X-ray source.

A redshift of $z = 1.15$ was reported by Hammer et al. (1995) based on UV/optical spectroscopy. In Figure 2, we display the combined spectrum obtained at Keck by Davis et al. (2003) using LRIS and DEIMOS. The presence of an AGN is clearly confirmed by the detection of [Ne V] and Mg II. There is, however, considerable self-absorption of the latter (Sarajedini et al. 2006), which prevents firm classification as a type 1 or a type 2 object. Interestingly, we also note the detection of Ca K and H absorption lines redshifted by ~150–200 km s^{-1} relative to [O II] and which suggests the presence of gas inflow in the galaxy.

Finally, mid-IR spectroscopy was carried out by Higdon et al. (2004) as well as our own group. We obtained[19] 960 s total exposure time for each of the two Short-Low (SL1: 7.4–14.5 μm; SL2: 5.2–8.7 μm) and each of the two Long-Low modules of the IRS (LL1: 19.5–38 μm, LL2: 14.0–21.3 μm; see Houck et al. 2004), while Higdon et al. (2004) targeted CXO J1417 for a total integration of 1440 s in LL1 and LL2. We reduced and combined all these data using the pipeline developed by the FEPS Legacy team (Hines et al. 2006), thus bringing the total integration to 2400 s for both LL1 and LL2. Our final spectrum covers the rest-frame 2.5–16.5 μm range. It is displayed in Figure 2 along with the X-ray spectrum of CXO J1417 obtained by Nandra et al. (2005).

TABLE 1

PHOTOMETRY OF CXO J1417

Band	Flux/Flux Density[a]	Refs.
2–10 keV	(3.8 ± 0. 3) × 10^{-14} ergs cm^{-2} s^{-1}	1
0.5–2 keV	(1.3 ± 0.1) × 10^{-14} ergs cm^{-2} s^{-1}	1
Far-UV (1539 Å)	<0.45 μJy (3 σ)	
Near-UV (2316 Å)	0.93 ± 0.15 μJy	
B (4389 Å)	0.8 ± 0.1 μJy	
R (6601 Å)	6.05 ± 0.15 μJy	
I (8133 Å)	16.7 ± 0.8 μJy	
J (1.2 μm)	57.6 ± 0.5 μJy	
K (2.2 μm)	117 ± 1 μJy	
IRAC 3.6 μm	580.1 ± 0.4 μJy	2, 3
IRAC 4.5 μm	981.7 ± 0.5 μJy	2, 3
IRAC 5.8 μm	1448 ± 4 μJy	2, 3
IRAC 8.0 μm	2225 ± 4 μJy	2, 3
IRS 16 μm	3.3 ± 0.7 mJy	4
MIPS 24 μm	5.75 ± 0.1 mJy	
MIPS 70 μm	20.1 ± 1.2 mJy	
MIPS 160 μm	105 ± 30 mJy	
SCUBA 850 μm	3.3 ± 1 mJy	5
VLA 5 GHz	53.6 ± 4 μJy	6
VLA 1.4 GHz	110 ± 40 μJy	6, 7, 8, 9

[a] Optical/near-IR fluxes are measured in a 1″ radius aperture.

REFERENCES.—(1) Nandra et al. 2005; (2) Barmby et al. 2006; (3) Ashby et al. 2006; (4) Higdon et al. 2004; (5) Eales et al. 2000; (6) Fomalont et al. 1991; (7) Webb et al. 2003; (8) Chapman et al. 2005; (9) Ivison et al. 2007.

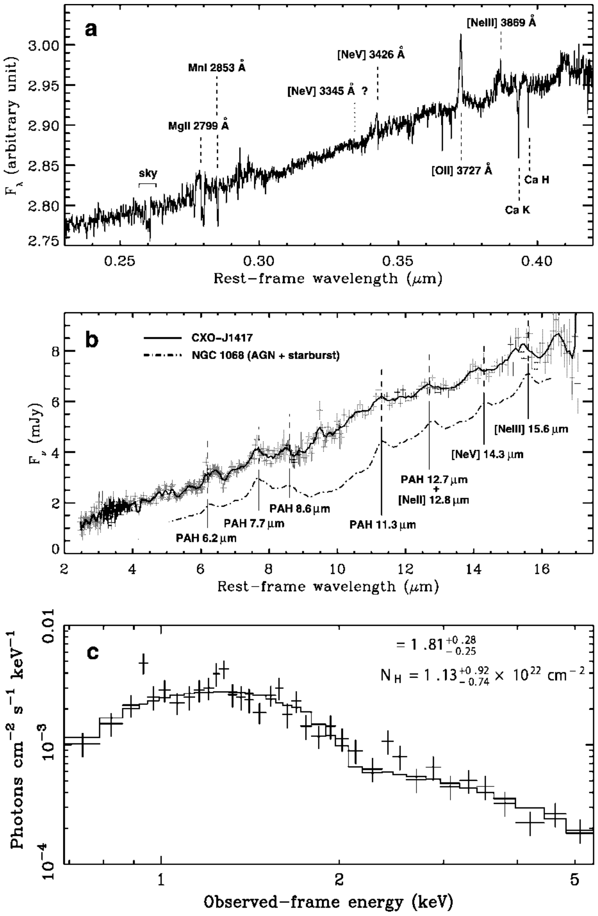

FIG. 2.—Optical (*a*), mid-IR (*b*), and X-ray (*c*) spectra of CXO J1417. The X-ray properties and the detection of [Ne V] λ3426 reveal the presence of an AGN that is also responsible for the hot dust emission and the featureless power-law SED in the mid-IR. The solid line in (*b*) is a smoothed version of the observed spectrum, while the dash-dotted line shows a comparison with the mid-IR SED of the Seyfert 2 NGC 1068. The solid line in (*c*) represents the best fit to the data, obtained with the parameters mentioned in the top right corner. In spite of the lack of strong silicate absorption at 9.7 μm, the column density derived at high energy indicates a significant obscuration toward the nucleus.

3. A PANCHROMATIC CHARACTERIZATION OF CXO J1417

The full SED of CXO J1417 is illustrated in Figure 3. It has a very red continuum with a steep rise from the optical up to the mid-IR, and the rest-frame 1.6 μm "bump" usually asso-

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[18] The FWHM of the MIPS PSF is 18″ and 40″ at 70 and 160 μm, respectively.

[19] General Observer program ID 3216.

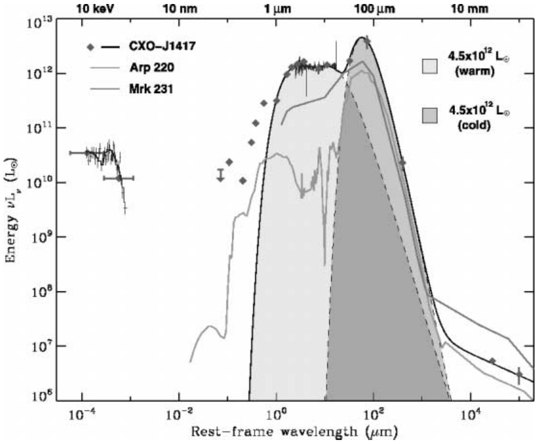

Fig. 3.—Panchromatic SED of CXO J1417 (*diamonds*) overlaid with a fit covering the X-ray, IR, and radio wavelength range (*solid black line*; see text for details). The X-ray and mid-IR spectra from *Chandra* and IRS are also displayed. The IR portion is fitted by a two-component model accounting for the warm (*light gray region*) and cold (*medium gray region*) dust emission. The fit in the radio assumes synchrotron emission with a spectral index $\alpha = 0.6$. The SEDs of Arp 220 and Mrk 231 (adapted from Silva et al. 2004, Spoon et al. 2004, and Ivison et al. 2004) are shown for comparison. [*See the electronic edition of the Journal for a color version of this figure*.]

ciated with stellar populations (Sawicki 2002) is not detected (Barmby et al. 2006; Ashby et al. 2006). The lack of this stellar feature and the very strong hot dust power-law emission that we observe at ~1–5 μm (see also Higdon et al. 2004) are characteristic of active nuclei (e.g., Brand et al. 2006). They reveal that the AGN totally dominates the luminosity of CXO J1417 at these short IR wavelengths.

We explored in more detail the properties of this active nucleus by fitting the X-ray spectrum with a power law intrinsically absorbed at $z = 1.15$ and assuming a Galactic extinction model. We derived a column density $N_{\rm H} = 1.13^{+0.92}_{-0.74} \times 10^{22}$ cm^{-2} and a photon index $\Gamma = 1.81^{+0.28}_{-0.25}$, leading to an extinction-corrected luminosity $L_{2\text{–}10\,\rm keV} = 2.35^{+0.30}_{-0.31} \times 10^{44}$ ergs s^{-1}. Although the lack of significant extinction by the silicates at 9.7 μm and the nondetection of the 400 eV iron Kα line indicate that it is not an extremely absorbed object, the X-ray data point therefore to a luminous AGN characterized by substantial obscuration.

This active nucleus is probably not the only source powering the bolometric luminosity of CXO J1417. Although they are strongly diluted by the continuum emission from the AGN, the mid-IR broad bands from the polycyclic aromatic hydrocarbons (PAHs) often seen in star-forming environments seem to be detected in our IRS spectrum (see Fig. 2*b*). Assuming a power-law continuum superimposed with a typical PAH template and leaving the redshift of the latter as a free parameter, we generated a series of simulated spectra that we compared to our data. The χ^2 shows a clear minimum when the PAH component is shifted to the distance of CXO J1417, which suggests that these features are detected with relatively good confidence.[20] Furthermore, the far-infrared and submillimeter detections reveal a very luminous cold dust component typical of those observed in dusty star-forming galaxies (see § 4). To quantify its contribution relative to the much warmer dust seen in the mid-IR, we decomposed the global IR SED beyond 1 μm into (1) a single modified blackbody[21] accounting for the cold component, characterized by a temperature $T \sim 40$ K and a dust emissivity $\beta \sim 1.7$, and (2) a combination of several blackbodies with temperatures ranging from 150 to 2000 K and reproducing the warm dust emission (see Fig. 3). We derived 1–1000 μm integrated luminosities of $4.5 \times 10^{12}\ L_\odot$ for each of these two components. This leads to a total IR luminosity $L_{1\text{–}1000\,\mu\rm m} = 9.0 \pm 0.4 \times 10^{12}\ L_\odot$, where the uncertainty is driven by the determination of the temperature and the emissivity of the cold dust emission.

CXO J1417 is also remarkably quiet in the radio. The spectral index ($\alpha \sim 0.6$) is typical of synchrotron emission from starbursts, although we cannot exclude a flatter continuum because of the substantial uncertainty on the observed flux density at 1.4 GHz. Assuming the standard far-IR/radio correlation (Condon 1992), we would infer an IR luminosity ~2.5 times lower than that implied by our fit of the cold dust component. As it has already been observed at low redshift (e.g., Rieke et al. 1980; Clemens & Alexander 2004; Gallimore & Beswick 2004), this radio faintness could result from substantial free-free absorption in the interstellar medium of the galaxy. It could also be due to a synchrotron deficiency characteristic of a very recent episode of star formation (Roussel et al. 2003).

4. DISCUSSION

4.1. *On the Nature of CXO J1417*

Although the bolometric correction for luminous and strongly absorbed X-ray sources has not been very well constrained so far, the obscuration toward CXO J1417 is still reasonable enough to allow a fairly secure estimate of the total luminosity of the active nucleus in this object. Comparison of the SED shown in Figure 3 with typical AGN templates (e.g., Elvis et al. 1994; Silva et al. 2004) indicates that this bolometric luminosity should typically range between 1×10^{12} and $3 \times 10^{12}\ L_\odot$. While the AGN can thus power most of the hot dust detected in the system, it is not energetic enough to account also for the far-IR emission. We argue that the cold dust component is produced by a deeply enshrouded starburst in the host galaxy (see also, e.g., Waskett et al. 2003). CXO J1417 could be therefore a high-redshift analog of some nearby "composite" ULIRGs where the contribution of the AGN to the bolometric output is comparable to that of the star-forming activity (Farrah et al. 2003). It could also be similar to other distant X-ray–selected sources that were detected at long wavelengths (e.g., Page et al. 2001), although this far-IR emission has been sometimes assumed to originate from the active nucleus rather than star formation (Barger et al. 2005).

When we assume the calibration from Kennicutt (1998), the IR luminosity of the cold component translates into a star formation rate SFR ~ 750 $M_\odot$ yr^{-1}. Such enhanced levels of activity usually occur within embedded and very compact regions surrounding the cores of galaxies (~100–300 pc; Soifer et al. 2000). It is consistent with the absence of direct star formation signatures as inferred from our UV/optical photometry as well as from the ACS image taking into account the spatial resolution of the *HST* data (i.e., ~1 kpc at $z = 1.15$).

4.2. *Implications*

If we assume a typical accretion efficiency $\epsilon = 0.1$ (Marconi et al. 2004), the luminosity of the AGN in CXO J1417 translates into a mass accretion rate $dM/dt \sim 3.1\ M_\odot$ yr^{-1}. This is typical of quasars at $z \sim 1$ (McLure & Dunlop 2004), but it is larger than the rates measured in sources experiencing similar levels of starburst activity such as the more distant SCUBA sources (Alexander et al. 2005). Furthermore, the bolometric luminosity of this object

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[20] At the redshift of CXO J1417, $z_0 = 1.15$, the χ^2 is reduced by a factor of ~2 with respect to its median value measured over a redshift range $z_0 \pm \Delta z$ with $\Delta z \sim 0.5$.

[21] We adopt the form $B_\nu(T)\nu^\beta$, where T is the dust temperature and β the dust emissivity.

and the obscuration toward its nucleus suggest that the gas fueling and the accretion are occurring quite efficiently, probably close to the Eddington limit. Under this hypothesis, we would derive a black hole mass of $\sim 1.4 \times 10^8\ M_\odot$. This is typically an order of magnitude larger than the mass of the SMBHs determined in the submillimeter galaxies, and it would be even larger in the case of a sub-Eddington accretion. These properties suggest that CXO J1417 is an object sharing characteristics with both starburst-dominated galaxies and quasars, where violent star formation is still happening while a massive black hole has already formed.

High-redshift ULIRGs showing a mixture of star formation and AGNs such as CXO J1417 could be interesting as tests of the evolutionary sequences that have been proposed to understand the connection between the two phenomena (e.g., Sanders et al. 1988). In such scenarios, for instance, merging galaxies first trigger powerful star formation, and as material settles into the cores of these objects it feeds a SMBH that eventually emerges as a luminous AGN. The latter can then produce strong winds and outflows that feed energy back into the surrounding galaxy and may either quench or reactivate star formation (Springel et al. 2005; Hopkins et al. 2005; Silk 2005). In the case of CXO J1417, there is a dominant contribution of the nucleus in the near-IR and it is not clear whether an underlying bulge has already formed in the host galaxy. However, sources experiencing star formation and disk accretion that both radiate a similar amount of energy throughout their lifetime would evolve toward massive galaxies that lie significantly out of the local "$M_{\rm BH}$-σ" relationship (Page et al. 2001). Although the starburst and the AGN in CXO J1417 are characterized by roughly equal luminosities now, we infer that if these two phenomena evolve together they may occur on quite different timescales and regulate each other efficiently for the bulges and SMBHs to grow in a coordinated manner.

Such transitional cases might be rare locally (e.g., Genzel et al. 1998). At higher redshift, however, their importance relative to the infrared/submillimeter or X-ray–selected objects where one type of activity (i.e., star formation or accretion) largely dominates is not yet known. Interestingly, CXO J1417 lies at the knee of the 2–8 keV luminosity function derived by Barger et al. (2005) at $0.8 \leq z \leq 1.2$, but it is much more IR-luminous than most of star-forming galaxies at this epoch of cosmic history (Le Floc'h et al. 2005). Searching for similar objects at higher redshifts when ULIRGs were a major component of the starbursting population (Blain et al. 2002) should allow us to explore in more detail the role that this coexistence of AGNs and starbursts within galaxies played in shaping the present-day universe. Even though their identification could be challenging, CXO J1417 points to the type of evidence required for this goal. Large data sets from existing surveys like AEGIS should provide this information for enough sources to probe the prevalence of this phase of galaxy evolution at $z \gtrsim 1$.

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