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EXOs: A Population of Dusty AGN in the Early Universe ⋆

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Abstract. Extreme X-ray / Optical sources ('EXO's) are a recently identified population of sources detected in deep XMM and Chandra surveys but with no strong detections of either the active galactic nucleus (AGN) or the host galaxies in deep optical imaging, thereby placing them at the extreme end of the Fx/Fopt plane with values about 100 times above typical AGN. The first Spitzer observations of these sources have provided clear detections of all of them, with SEDs indicative of highly reddened and underluminous galaxies at redshifts in the range 3 - 6 or above. The reddening is likely due to dust from intense star-formation that may also be linked to increased accretion onto the central black hole, hence these objects provide a unique probe of the relationship between black holes and galaxy growth in the early universe.

Key words. X-rays: galaxies — galaxies: active — galaxies: evolution — galaxies: high-redshift — surveys

1. Introduction

A key question in astrophysics concerns the evolution of active galactic nuclei (AGN) during the "quasar epoch" and earlier ($z \sim 2-6$), where their space density evolves rapidly (Fan et al. 2001, 2003; Barger et al. 2003). Their evolution appears to track the star formation rate (e.g., Steidel et al. 1999), thereby suggesting an empirical link between galaxy

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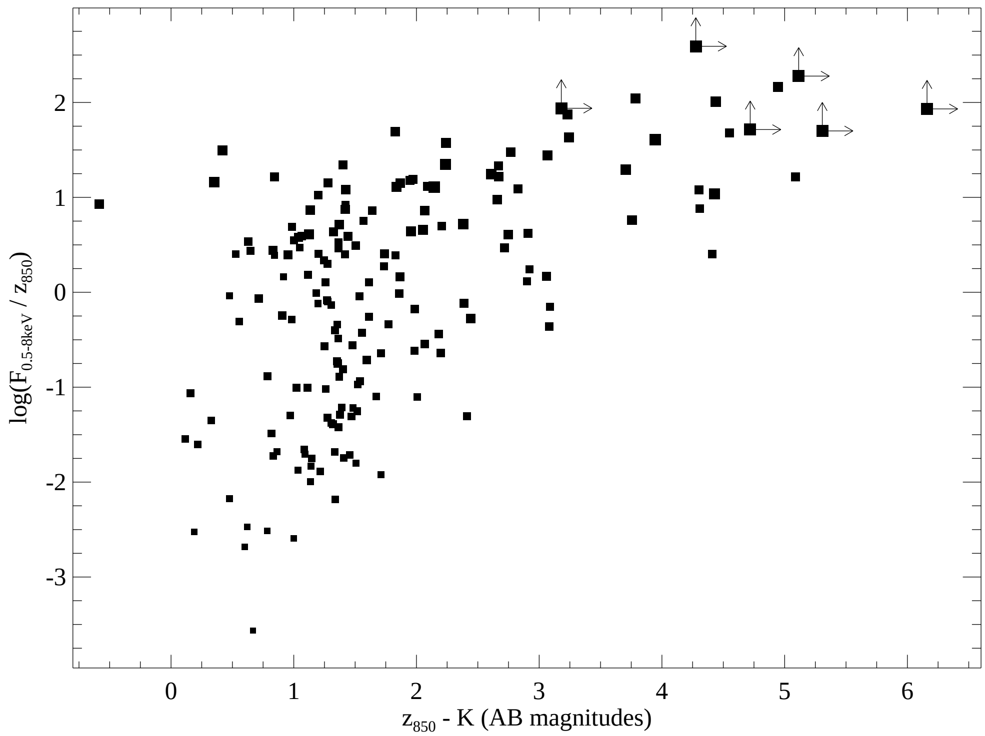

Fig. 1. Ratio of $F_{0.5-8\,\mathrm{keV}}$ to z_{850} flux for all the CDFS X-ray sources, plotted against $z_{850} - K$. Symbols size represents z_{850} magnitude, fainter sources being larger. Note in particular that redder objects generally tend to have higher F_X/F_{opt}.

growth and AGN fuelling. A connection between galaxies and AGN is also suggested by the black hole / bulge mass relationship (Ferrarese & Merritt 2000; Gebhardt et al. 2000).

X-ray emission provides a powerful tool to investigate such relationshis since it directly tracks AGN accretion luminosity. Ultra-deep *Chandra* X-ray surveys on the Hubble Deep Field North (HDFN; Brandt et al. 2001), and Chandra Deep Field South (CDFS; Giacconi et al. 2002) are sufficiently sensitive to reveal AGN up to cosmological distances. The GOODS survey (Giavalisco et al. 2004; Dickinson et al. 2004) obtained multi-band coverage on these fields with *Hubble*, *Spitzer*, and large ground-based telescopes, providing deep images across a wide wavelength range.

In particular, an interesting class of sources discovered from these surveys are sources with extreme X-ray / Optical flux ratios (*"EXO"*s, Koekemoer et al. 2004), that are detected in X-rays and the near-IR, but completely undetected in the optical to $m(AB) \sim 28$. They are all detected in the mid-IR by *Spitzer*, and here we discuss possible interpretations for them and their relationship to AGN evolution. Throughout this paper we adopt a standard ΛCDM cosmology.

2. Selection of EXO's

The EXO's in the CDFS were identified by matching the X-ray catalogs (Alexander et al. 2003) to the ACS z_{850} catalogs (Giavalisco et al. 2004), and are shown in Figure 1. Most of the 225 X-ray sources in the ACS field have optical counterparts, and consist either of moderate-luminosity AGN or star-forming galaxies. However, 7 of the X-ray sources have

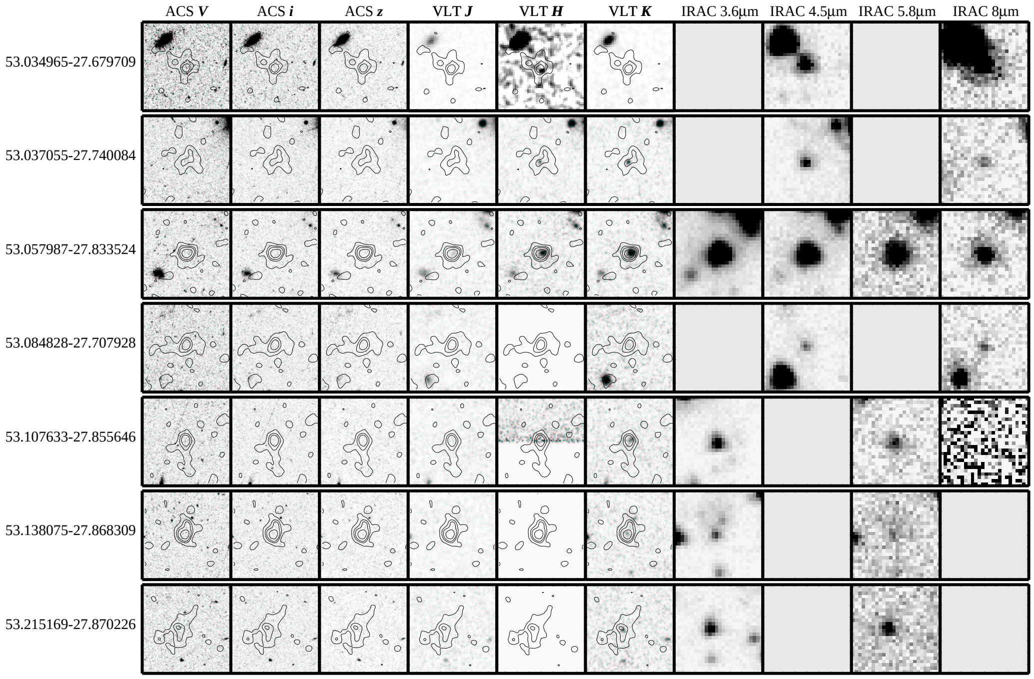

Fig. 2. The 7 EXO's in CDFS (Koekemoer et al. 2004), showing the ACS non-detections as well as the VLT JHK images. Each panel is 15″ on a side, with contours showing the $0.5-8$ keV *Chandra* detections. We also show the *Spitzer* IRAC images, which readily detect all the EXO's.

no ACS counterparts; furthermore, when their X-ray fluxes are compared with their optical limits, they are found to have a ratio of $F_{0.5-8\,\mathrm{keV}}/F_{z850}$ 100, at least an order of magnitude above most AGN. In Figure 1 we also plot our measured ACS magnitudes for CDFS sources reported as undetected in ground-based data by Yan et al. (2003), and show Extremely Red Objects (EROs) from previous studies (Alexander et al. 2002; Koekemoer et al. 2002; Stevens et al. 2003).

Six of the EXO's are detected in K-band with $AB(K) \sim 22-24$, thus their $z-K$ colours are redder than almost all the other X-ray sources, with $z_{850}-K > 4.2-6.2$. Both their high X-ray/optical ratios and their red colours are interesting, since it is not expected *a priori* that optically undetected objects should have strong X-ray flux, nor that they should be particularly red (see also Brusa et al. 2002; Cagnoni et al. 2002).

Our recent *Spitzer* observations of the CDFS were obtained using the IRAC instrument in all four channels: 3.6, 4.5, 5.8, 8 μm. In the first epoch, most of the field was covered by only two bands (either 3.6 and 5.8 μm, or 4.5 and 8 μm), with only one EXO covered by all 4 channels. However, it is clear that all the EXO's are readily detected by *Spitzer*, as shown in Figure 2.

3. Possible Constituents of the "EXO" Population

Using our optical, near-IR and *Spitzer* data, we have carried out some preliminary SED modelling of the EXO's in order to investigate their nature. The fundamental observational features that need to be explained are: (1) their extremely red optical/near-IR colours; (2) their red near-IR/mid-IR colours; and (3) their colours as measured within IRAC, most of which are red although one or two of the sources have flat or blue spectra within IRAC. Since we observe no optical flux at all, it is highly unlikely that any of these objects are Type 1 unobscured AGN, since their X-ray flux is relatively bright and some optical flux would have been expected. Therefore, we consider a scenario where the light from the AGN itself is obscured and the emisison is dominated by the host galaxy, thus we aim to understand these objects by modelling their host galaxy stellar populations.

We find that in general, the EXO's are well fit by sources at $z \sim 2-5$, with either an evolved single-burst population or a younger reddened star-forming population. A common feature of the best-fitting models is that the stellar mass is relatively low when compared with the host galaxies of most other AGN of similar X-ray luminosity: their stellar masses tend to lie in the range $\sim 10^9 - 10^{10} M_{\odot}$. Their X-ray luminosities are in the range $L_X \sim 10^{44} - 10^{45}$ erg s^{-1}, and locally AGN of this luminosity tend to be found in galaxies with a mass $\sim 10^{11} M_{\odot}$, thus the EXO host galaxies appear to be about a factor of 10 intrinsically under-luminous, or under-massive, compared to what would be expected based on their X-ray luminosity.

We note that one of the objects is not well fitted by any stellar models with redshifts below $z \sim 6-7$; if fit with a $z \sim 7$ dusty starburst, its mass is $\sim 10^{10} M_{\odot}$. This source has much redder IRAC colours than any of the other EXO's, which is what drives the SED constraints. However, our near-IR data on this source are not as deep as some of the other EXO's, and we aim to obtain further data on this source in order to investigate it further.

Thus, the majority of the EXO's appear to be explained by relatively under-luminous, or under-massive, host galaxies compared with their X-ray emission, or conversely, their X-ray emission appears enhanced over what woudl normally be expected. A possible explanation for this may be a period of increased AGN luminosity, perhaps related to the dusty star-forming activity that seems to be indicated by the SEDs. If this is the case, then these objects may be tracing enhanced AGN accretion at high redshift associated with galaxy interaction events.

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