Extragalactic jets from every angle
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X-ray jets and nuclear emission in low redshift early-type galaxies

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Abstract. Due to its high angular resolution, the Chandra Observatory has allowed the discovery and detailed study of extragalactic X-ray jets. Although supermassive black holes are regularly found in the cores of massive galaxies and X-ray emission is detected from ∼80% of these, X-ray and radio jets are only detected in a small fraction of "normal" galaxies. X-ray jets are either single-sided or double-sided and, with only one possible exception, are found to have radio emission. However many radio jets are not detected in current X-ray observations. The expanding jets produce cavities in the surrounding hot gas in the galaxy halos. By determining how much gas has been pushed out of these cavities, we can determine the mechanical energy and power of the jet.

Keywords. galaxies: jets, galaxies: nuclei, X-rays: galaxies

1. Introduction

Prior to the launch of the Chandra X-ray Observatory, only four X-ray jets had been discovered. The spatial resolution of the Einstein HRI and ROSAT HRI instruments allowed X-ray jets to be found in Centaurus A (Feigelson *et al.* 1981), M87 (Schreier, Gorenstein & Felgelson 1982), 3C120 (Harris *et al.* 1999) and 3C273 (Willingale 1981). Chandra's sensitivity and arcsecond spatial resolution truly opened the study of extragalactic X-ray jets. Our choice of the first celestial target for the Chandra focusing observations was constrained by the initial limits on the satellite maneuvers. In the allowed region of the sky, we used ROSAT observations to select a "point" X-ray source that was not too bright and not too faint. To our surprise and delight, this observation resulted in the *Chandra Discovery of a 100 kpc X-ray Jet in PKS0637-752* (Schwartz *et al.* 2000). Fortunately the separation of the bright X-ray nucleus and the jet still allowed us to verify Chandra's focus.

Before the launch of Chandra, we also selected a few targets whose Chandra observations would be immediately released to the community to provide examples for future observers. These targets could not already be in the scientific programs of the Chandra instrument teams or the interdisciplinary scientists. Two of the targets we selected were

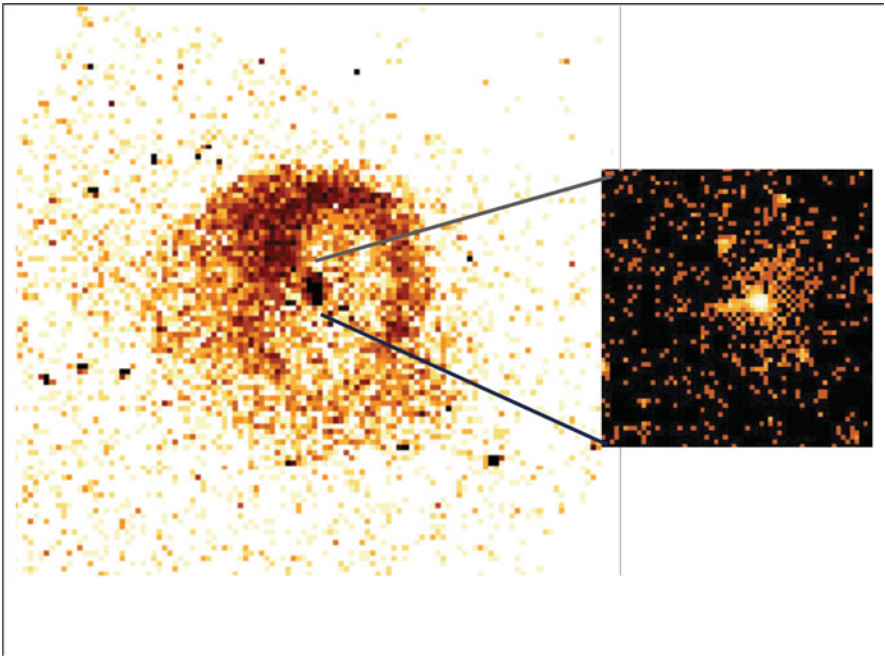

Figure 1. (left) The Chandra X-ray image of UGC408 shows a large 20 kpc cavity around the galaxy nucleus. (right) The central region of UGC408 shows X-ray emission from the core, an X-ray jet extending east from the nucleus, a small gas corona, and compact X-ray sources in the galaxy. See Bogdan *et al.* (2014) for additional details.

Centaurus A and Hydra A. These observations of these two sources were remarkable and, along with with many early GO observations, opened the new field of X-ray research on jets. The Chandra observation of Centaurus A showed the complex of numerous X-ray knots in the jet (Kraft *et al.* 2000), while the observation of Hydra A showed X-ray cavities in the surrounding hot gas, which were also filled with radio emission (McNamara *et al.* 2000). The fact that Centaurus A and Hydra A were not in the programs of the instrument teams or interdisciplinary scientists further demonstrates how little was known before Chandra about extragalactic X-ray jets. See Worrall (2009) for a review of Chandra's impact on our understanding of extragalactic jets.

2. Overview

In the core of nearly every massive galaxy lies a supermassive black hole. Galaxies hosting 3C radio sources are often found to have X-ray as well as radio jets eminating from their supermassive blackholes (e.g., NGC 315 Worrall *et al.* 2007; NGC383 Hardcastle *et al.* 2002). The hot X-ray emitting gas in galaxies, as well as in groups and clusters, provides a fossil record of the AGN activity and is often the primary record of recent AGN outbursts. Chandra observations have shown that AGN-produced cavities in the hot gas in clusters, groups and galaxies are relatively common. In particular Dunn and Fabian (2006) found that 70% of cool-core clusters exhibit X-ray cavities in their hot gas. In Chandra X-ray observations of a sample of $\sim$ 200 nearby "normal" massive early-type galaxies surrounded by hot coronae, we found that $\sim$ 30% have cavities in their hot atmospheres (Nulsen *et al.* 2009).

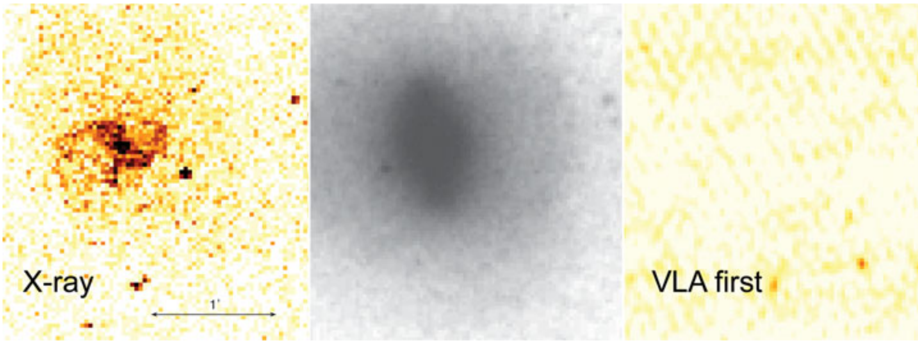

Figure 2. (left) The Chandra X-ray image of NGC4477 shows an X-ray bright nucleus and two cavities to the east and west. (center) The optical DSS image of the galaxy on the same scale as the X-ray image. (right) The VLA FIRST image of NGC4477, on the same scale as the X-ray and optical images, shows no radio emission from the nucleus or the two X-ray cavities.

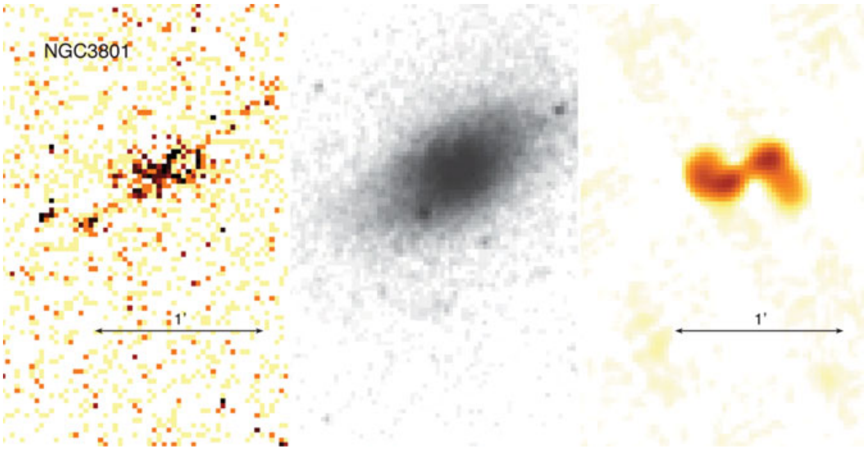

Figure 3. (left panel) The Chandra X-ray image of NGC3801 shows two inner cavities centered on the X-ray bright nucleus and two X-ray jets extending NW and SE. (center panel) The optical image of the SO galaxy NGC3801. (right panel) The VLA FIRST image of NGC3801 shows the bright radio lobe emission that fills the X-ray cavities. See Croston, Kraft, & Hardcastle (2007) for a more detailed discussion.

The size and number of cavities in the hot gas varies from one galaxy to another. As examples, NGC4636 and NGC4552 each show two primary cavities (Jones *et al.* 2002, Baldi *et al.* 2009, Machacek *et al.* 2006), while M84 and the NGC5813 group show multiple cavities aligned along a single axis through the nucleus (Finoguenov *et al.* 2008, Randall *et al.* 2011). The cavity morphology of the group NGC5044 exhibits multiple cavities throughout its hot gas (David *et al.* 2009). A somewhat different morphology is seen in the Chandra image of UGC408 (see Fig. 1) which shows a large (~ 20 kpc) cavity around the nucleus, likely produced by two AGN outbursts, as well as an X-ray jet aligned with the radio jet extending east of the nucleus (Bogdan *et al.* 2014).

The radio morphology of early type galaxies can range from radio lobes which fill the X-ray cavities, as found for M84 (Finoguenov *et al.* 2008), NGC5813 (Randall *et al.* 2011), and UGC408 (Bogdan *et al.* 2014), to X-ray cavities which show little or no associated radio emission, such as the two cavities in NGC4477 (see Fig. 2), and several of the X-ray cavities in NGC5044 (David *et al.* 2009).

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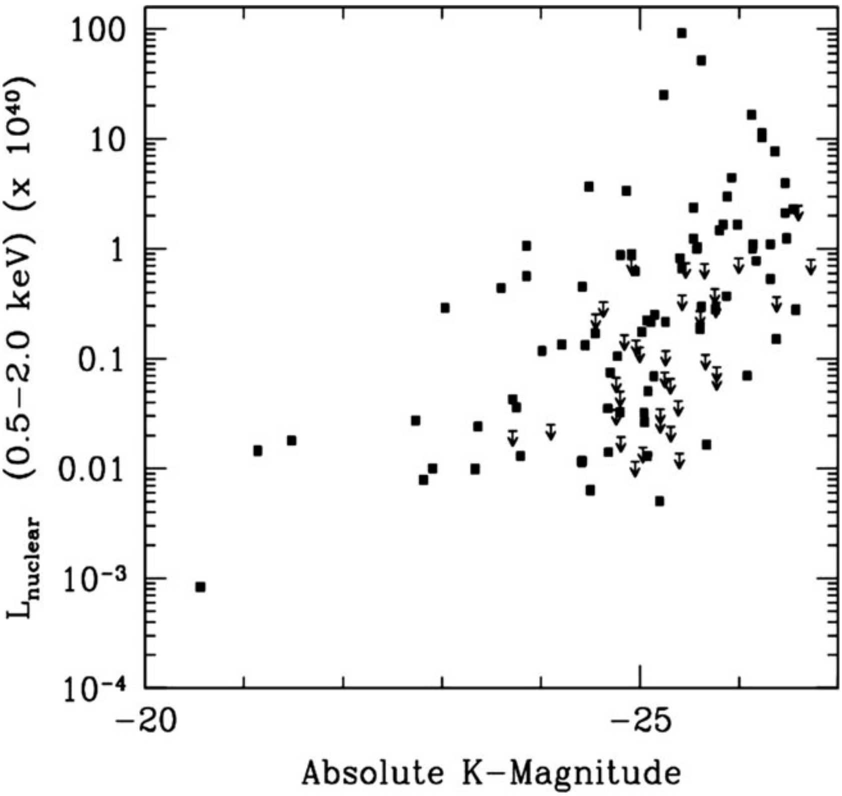

Figure 4. Nuclear Xray emission is detected from ∼80% of early type galaxies. Here we plot each galaxy's absolute magnitude against its nuclear X-ray luminosity measured from Chandra observations. Upper limits are shown with a downward pointing arrow.

The morphologies of the X-ray jets include single-sided jets (e.g. UGC408 (Bogdan *et al.* 2014) and double-sided jets (e.g. NGC4261 (Worrall *et al.* 2010, O'Sullivan *et al.* 2011, Massaro *et al.* 2013). Among the more unusual X-ray jets is the double-sided X-ray jet-like structure in NGC3801, which appears to be aligned with the inner radio jets, but extends beyond the X-ray cavities and the radio emission which fills those cavities (see Figure 3) (Croston, Kraft, & Hardcastle 2007). Croston *et al.* (2007) suggest the X-ray jet structure is a tidal or ram pressure stripped tail produced by the interaction of NGC3801 with a nearby galaxy. Note also that for NGC3801, Emonts *et al.* (2012) reported a large HI disk perpendicular to an inner CO disk and dust lane, supporting the suggestion that NGC3801 has experienced a gas-rich galaxy merger.

In some of the galaxies that have been studied, although cavities in the hot gas are found, neither radio or X-ray jets have been detected (e.g. NGC5813).

While the detection of X-ray and radio jets in early-type galaxies is relatively rare, nearly 80% of the nearly 200 early-type galaxies we have studied show X-ray emission from their nuclei, (see Fig. 4) which plots each galaxy's absolute optical magnitude against its nuclear X-ray luminosity. We used the 2MASS catalog (Skruskie *et al.* 2006) and images available through the SAOimage ds9 data visualization tool to identify that the X-ray point source was most likely identified with the galaxy nucleus and not with a nearby galactic X-ray binary that might appear near the nucleus. The X-ray luminosities of the nuclei of these galaxies range from 10^{37} to 10^{42} ergs s^{-1} in the energy range from 0.5 to 2 keV.

3. Implications

The impacts of supermassive black holes on early-type galaxies. The energy carried by jets from the supermassive black hole plays a fundamental role in the evolution of galaxies. The feedback produced by the AGN outflows is critical for reheating, or occasionally expelling (see Lanz *et al.* (2010)), cooling gas in the cores of galaxies, thus truncating new star formation which prevents the formation of more massive galaxies than are observed, while maintaining the “red and dead” nature of early type galaxies. X-ray observations, along with radio and optical studies and simulations are crucial for understanding how the jets are fueled as well as for understanding how the jets inflate the cavities and how the energy is transferred to the surrounding gas.

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