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Dual Active Galactic Nuclei

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Abstract. We still do not know the timescale for the merging of binary black holes (BHs). This timescale has important implications for gravitational wave predictions and our understanding of BH demographics. Here we discuss efforts to constrain the fraction of BH pairs on kpc scales using observations of dual active galactic nuclei.

Keywords. supermassive black holes, active galactic nuclei, binary black holes

1. Introduction

We live in a hierarchical universe, where structures collapse as small units and then grow by merging. We see direct evidence of these mergers in the galaxy population. We also know that most, if not all, massive galaxies today harbor supermassive black holes (BHs) at their centers. The question then becomes, what happens to the pair of BHs during and after a merger?

We know that the two BHs will sink to the center of the potential via dynamical friction, and then the binary will harden via three-body interactions with stars. However, in an axisymmetric potential, at separations of ~ 1 pc it is possible that the BHs may run out of stars to scatter, and stall (e.g., Begelman *et al.* 1980; Quinlan 1996). In principle, there may be pc-scale binary BHs lurking in the centers of many galaxies. From a theoretical perspective, thirty years of debate has not settled the issue of whether binary BHs stall (e.g., Gould & Rix 2000; Merritt & Poon 2004; Yu *et al.* 2005; Armitage & Natarajan 2005; Merritt & Milosavljević 2005; Tremmel *et al.* 2015). Observationally we cannot rule out that BHs stall at pc scales, because it is so difficult to spatially resolve pairs of BHs on such small scales. There is really only one iron-clad case of a binary BH with a 7 pc separation where we have imaging of a BH pair (Maness *et al.* 2004; Rodriguez *et al.* 2006).

However, many things depend on the timescale for binary BH mergers. For one thing, the detectability of low-frequency gravitational radiation (e.g., with pulsar timing arrays; see other contributions in this volume) depends sensitively on the merger timescale of BH binaries. The overall growth rate of BHs and the distribution of BH spin depends on the merger rate (e.g., Volonteri *et al.* 2005). The importance of the so-called gravitational slingshot effect, in which anisotropic gravitational radiation from unequal BH binaries imparts a net linear momentum to a merged remnant, also depends on the merger timescale. While people have looked for ejected BHs (e.g., Hoffman & Loeb 2006; Civano *et al.* 2010), it is not clear that any have been found.

This article takes a step back from pc-scale binary BHs and asks whether we can put interesting constraints on the BH merger rate using observations of pairs of BHs on kpc scales.These so-called dual AGN are special cases where a pair of BHs are both activated presumably during or following a merger. A number of studies have shown that a galaxy is more likely to be an AGN if it is in a galaxy pair with separations of 5–20 kpc (Ellison

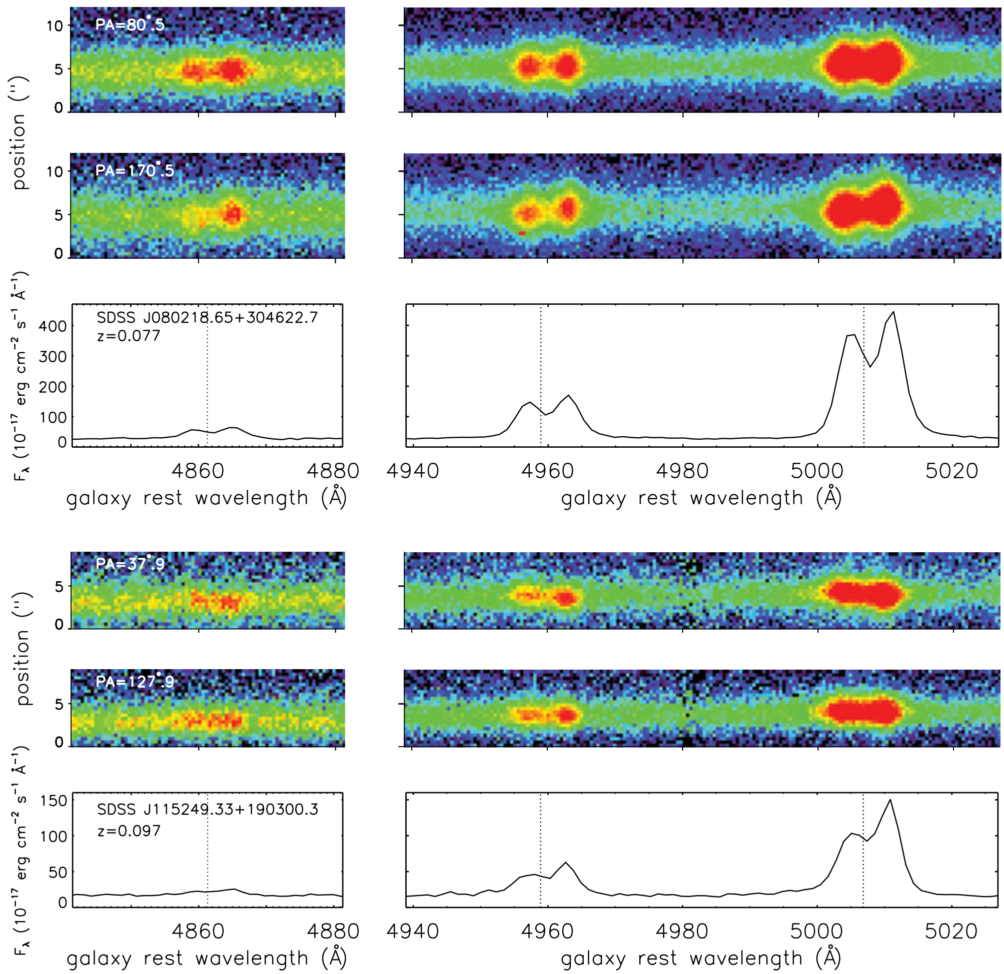

Figure 1. Example two-dimensional spectra (color) and one-dimensional SDSS spectra for some probably dual AGN adapted from (Comerford *et al.* 2009a).

et al. 2011; Silverman *et al.* 2011). However, to probe yet smaller scales (<kpc) is difficult with ground-based imaging, corresponding to sub-arcsecond separations at $z = 0.1$.

We will briefly summarize observational programs to find dual AGN with ∼kpc separations. We will then focus on the close cousins of dual AGN, the offset AGN. Then we will discuss future searches. Finally, we discuss one spectroscopic method for putting limits on binary BHs.

2. Search for Dual Active Galaxies

Pairs of accreting BHs with kpc separations could be distinguished in a number of ways. For instance, one might find two blue nuclei, pointing to a pair of unobscured quasars (e.g., Myers *et al.* 2008; Hennawi *et al.* 2010; Liu *et al.* 2011). Alternately, one might find two X-ray or radio cores (e.g., Rodriguez *et al.* 2006). Finally, one might identify them spectroscopically, via their orbital motions. A handful of such objects were known (e.g., Komossa *et al.* 2003; Koss *et al.* 2011). The Sloan Digital Sky Survey (SDSS, York *et al.* 2000) performed a uniform survey of galaxies and AGN, which allows for spectroscopic

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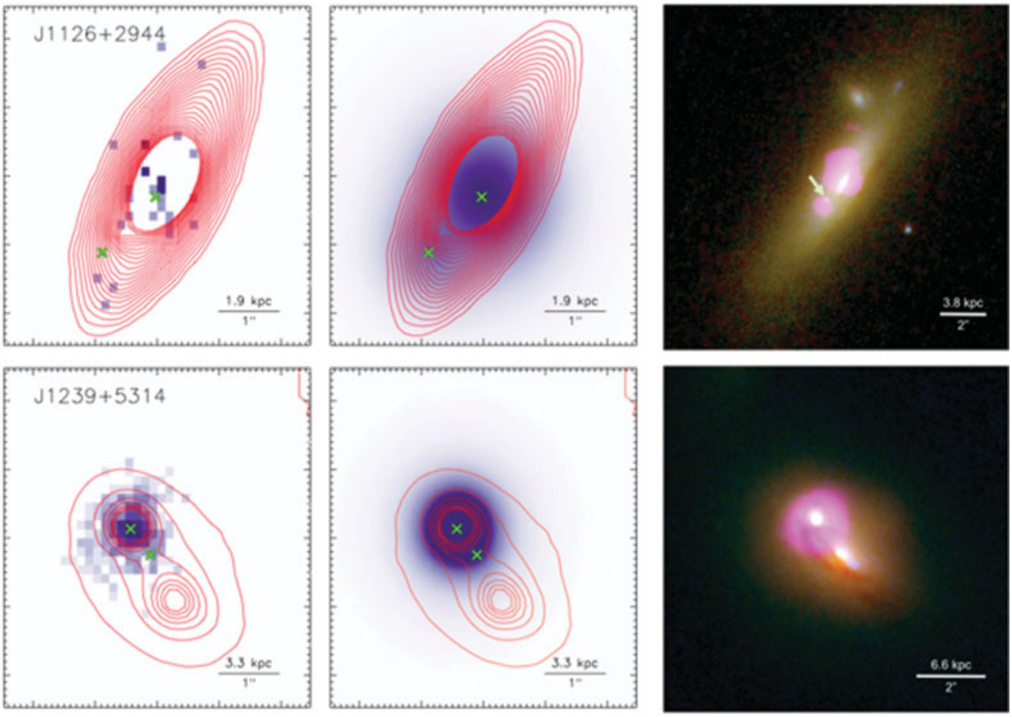

Figure 2. Dual AGN system (top) and an offset or dual AGN system (bottom) identified from follow-up Chandra observations, adapted from Comerford *et al.* (2015).

selection of possible dual AGN. Specifically, orbital motion could lead to velocity splitting of the narrow emission lines for kpc-scale separations (Figure 1).

2.1. *Spectroscopic Samples*

In fact, $\sim 10\%$ of low-redshift AGN show velocity splitting in their narrow emission lines (Heckman *et al.* 1981; Veilleux 1991; Comerford *et al.* 2009a; Wang *et al.* 2009; Liu *et al.* 2010b; Smith *et al.* 2010). Examples of these "double-peaked" AGN are shown in Figure 1. Hundreds of potential dual AGN were found in SDSS. The next obvious question becomes, are these in fact AGN pairs, or are the multiple velocity peaks in the SDSS spectra caused by other things. Recall that the SDSS I/II fibers were $3''$ in diameter, encompassing roughly 5 kpc at the typical redshift of $z \approx 0.1$ of the SDSS main galaxy sample. Thus, outflows and rotating disks make significant contributions to the double peaked sample (Crenshaw *et al.* 2010).

The first attempts to determine the nature of these sources used long-slit spectroscopy and NIR imaging (Liu *et al.* 2010a; Shen *et al.* 2011; McGurk *et al.* 2011; Comerford *et al.* 2012; Ge *et al.* 2012). Roughly 10% of double-peaked systems have line emission aligned with two NIR continuum peaks that indicate bona-fide dual systems. This translates to 1% of all low-redshift AGN in SDSS being part of a dual AGN system.

2.2. *X-ray Follow-up*

In principle, hard X-rays should be able to penetrate even very significant absorption and provide a more reliable view of dual AGN (Figure 2). In practice, the X-ray luminosities have proved systematically lower than expected, making X-ray followup far more expensive than expected (Comerford *et al.* 2011; Liu *et al.* 2013; Comerford *et al.* 2015).

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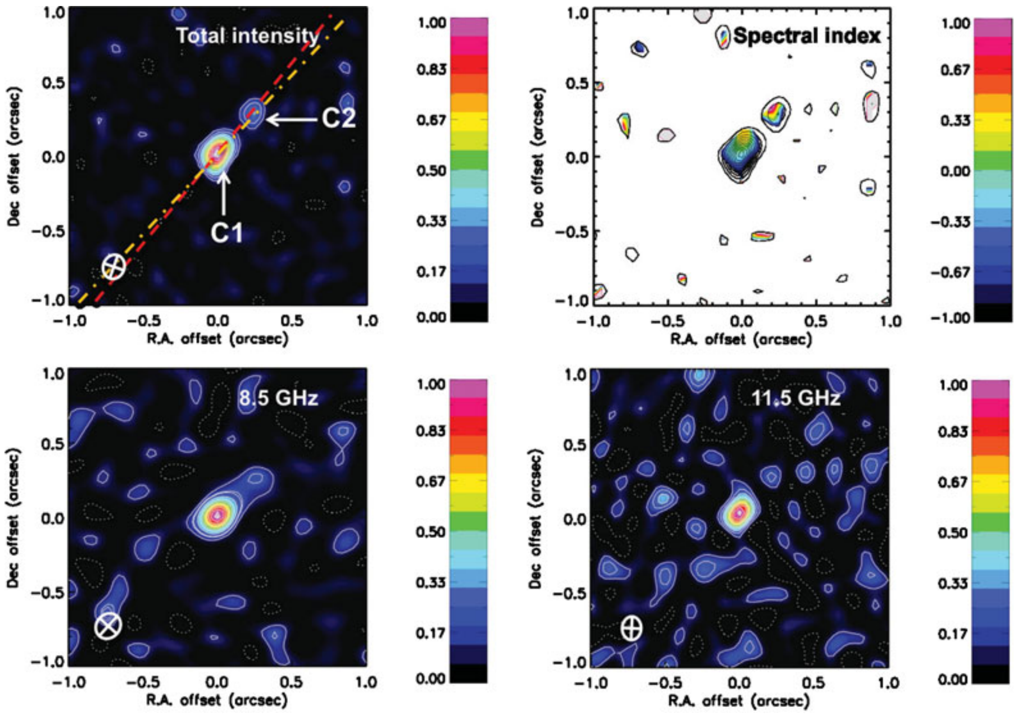

Figure 3. Compelling dual AGN system based on follow-up JVLA observations, adapted from Muller-Sanchez *et al.* (2015).

2.3. *Radio Follow-up*

With the advent of the EVLA, radio follow-up became a very efficient method to search for true dual AGN (Rosario *et al.* 2010; Fu *et al.* 2011; An *et al.* 2013). Müller-Sanchez *et al.* (2015) have just performed a uniform survey of double-peaked AGN using EVLA, to find a dual AGN rate of $\sim$ 10–15% (Figure 3). This rate is roughly consistent with the earlier spectroscopic follow-up studies, but is likely more robust, since from the radio imaging+spectroscopy it is possible to find likely jets as well as dual cores.

3. Offset AGN

A complementary approach to understanding the role of merging in AGN triggering and BH growth is to look for cases of velocity offsets between stellar absorption features and AGN emission lines (see examples in Figure 4). These offset AGN may be a signpost of an inspiraling accreting BH on kpc scales. There have been a few serendipitous detections of such systems (Barth *et al.* 2008; Bianchi *et al.* 2013). However, Comerford *et al.* (2009a) performed the first systematic search for such systems at intermediate redshift using the DEEP2 survey. They found velocity offsets were quite common (30%) at these redshifts. To see whether this trend persists at lower redshift, she performed two additional searches (Comerford *et al.* 2013; Comerford & Greene 2014). Follow-up of these sources is ongoing, but the initial estimate is that the offset AGN fraction increases from 2%–30% from the present to $z \sim 0.7$.

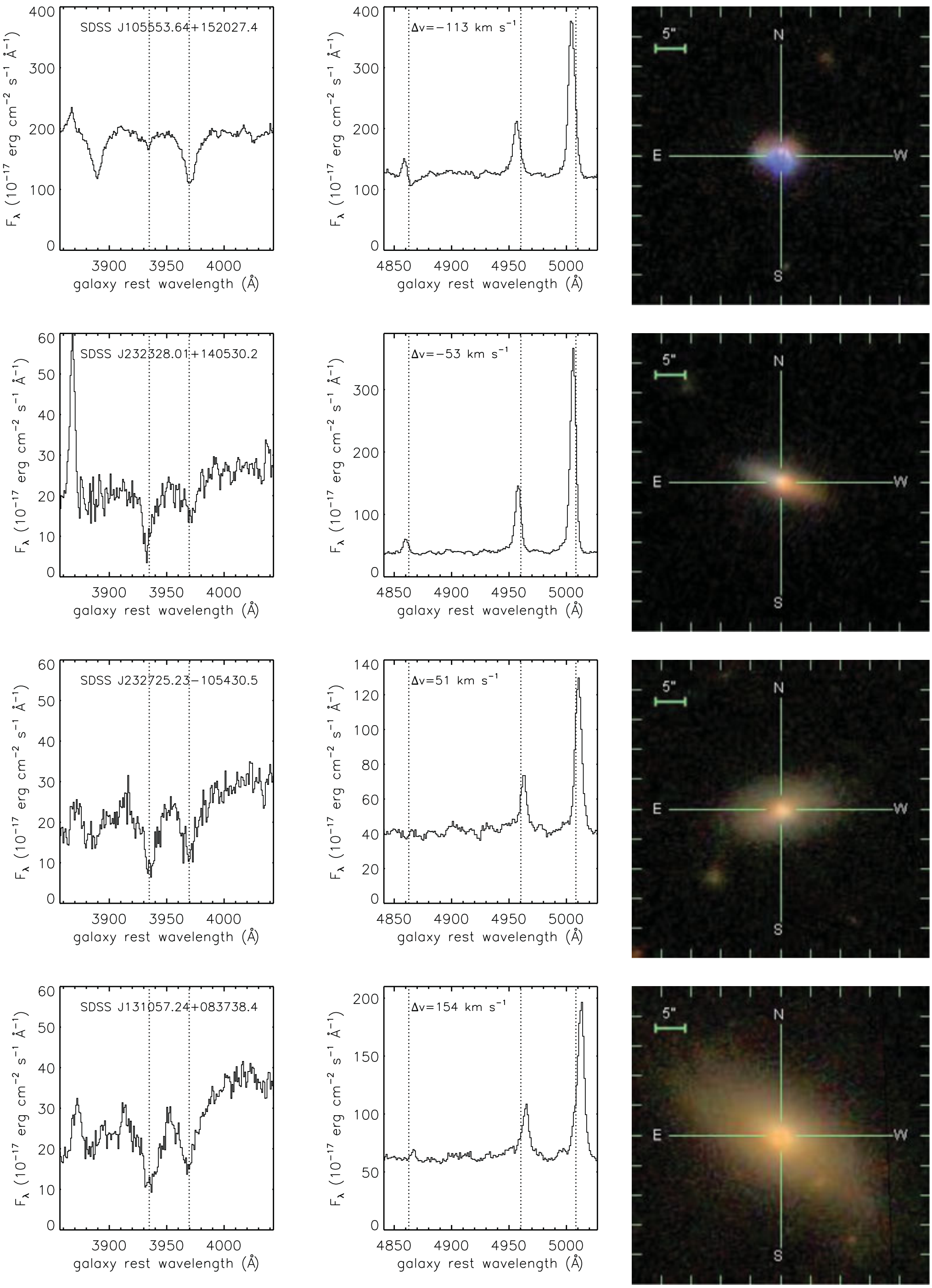

Figure 4. Examples of offset AGN candidates, showing that the narrow emission lines show consistent velocity offsets when compared with the stellar absorption lines. Adapted from Comerford & Greene (2014).

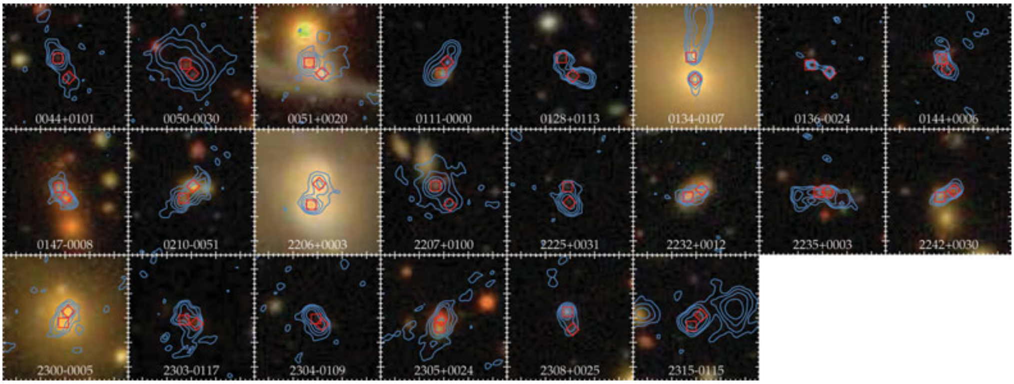

Figure 5. The possibility of finding dual AGN in the radio directly adapted from Fu *et al.* (2015). From a pilot follow-up survey, Fu *et al.* estimate 60% of their candidates will be true dual AGN.

4. The Future

While double-peaked sources are intriguing, they have not proved a very efficient method for finding dual AGN (only 10% are true dual AGN). It is interesting to think about alternate search methods. One is to start by detecting dual galaxy cores, and then following these up to see how many harbor dual AGN (Comerford *et al.* 2009b, 2011; Lackner *et al.* 2014). Another is to search directly in the radio for dual cores (Fu *et al.* 2015, Figure 5). It is early days for these alternate searches, so stay tuned for the true dual AGN space density!

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