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Modeling the Observability of Recoiling Black Holes as Offset Quasars

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Abstract. The merger of two supermassive black holes (SMBHs) imparts a gravitational-wave (GW) recoil kick to the remnant SMBH, which can even eject the SMBH from its host galaxy. An actively-accreting, recoiling SMBH may be observable as an offset quasar. Prior to the advent of a space-based GW observatory, detections of these offset quasars may offer the best chance for identifying recent SMBH mergers. Indeed, observational searches for recoiling quasars have already identified several promising candidates. However, systematic searches for recoils are currently hampered by large uncertainties regarding how often offset quasars should be observable and where they are most likely to be found. Motivated by this, we have developed a model for recoiling quasars in a cosmological framework, utilizing information about the progenitor galaxies from the Illustris cosmological hydrodynamic simulations. For the first time, we model the effects of BH spin alignment and recoil dynamics based on the gas-richness of host galaxies. We predict that if BH spins are not highly aligned, seeing-limited observations could resolve offset AGN, making them promising targets for all-sky surveys. The rarity of large broad-line offsets among SDSS quasars is likely due in part to selection effects but suggests that spin alignment plays a role in suppressing recoils. Nonetheless, in our most physically motivated model where alignment occurs only in gas-rich mergers, hundreds of offset AGN should be found in all-sky surveys. Our findings strongly motivate a dedicated search for recoiling AGN.

Keywords. accretion, accretion discs – black hole physics – gravitational waves – hydrodynamics – galaxies: active – galaxies: interactions

1. Introduction

Supermassive black hole (SMBH) binary mergers release a vast amount of energy in gravitational waves (GWs). Any asymmetry in the merging BH system will impart a "recoil kick" to the merged BH, which can eject the BH from its host galaxy (e.g., Campanelli *et al.* 2007). Recoiling BHs could be observed as a spatially- or kinematicallly-offset quasars. In the last few years, a handful of candidate recoiling quasars have been identified (e.g., Komossa *et al.* 2008; Civano *et al.* 2010; Koss *et al.* 2014), but none have yet been confirmed. Systematic searches for recoiling BHs have been hampered by large uncertainties regarding pre-merger BH spins and the influence of gas on recoil dynamics. We construct a model for the observability of offset quasars, utilizing data from the Illustris cosmological hydrodynamic simulations (e.g., Vogelsberger *et al.* 2014).

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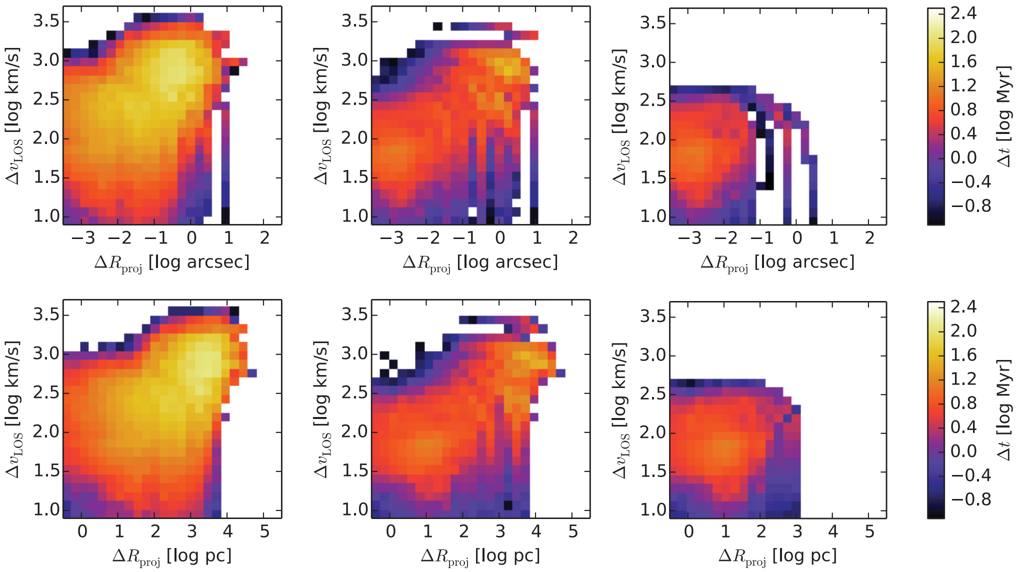

Figure 1. Time-weighted distributions of projected spatial vs. line-of-sight velocity offset are shown for all recoiling quasars. The color scale indicates offset quasar lifetime, assuming the sensitivity of *HST*-COSMOS. The *top (bottom) panels* show angular (physical) spatial offsets. The *left panels* assume randomly-oriented spins, *middle panels* assume a "hybrid" model where spins are aligned only in gas-rich mergers, and *right panels* assume nearly-aligned spins. Large offsets are *favored* in the random spin model but do not occur at all if spins are nearly aligned.

2. A Model for Recoiling Quasars

To model the observability of recoiling quasars, we extract BH and galaxy merger data from the Illustris simulations. We assign a kick velocity assuming a BH spin distribution, integrate the BH trajectory in the host potential, and calculate the quasar luminosity.

Figure 1 shows the distributions of recoiling AGN offsets. We see that large offsets are favored as long as spins are not highly aligned. In particular, in the random and hybrid spin models, seeing-limited observations could resolve spatially-offset AGN.

3. Conclusions

We find that spatially- and velocity offset AGN are promising targets for all-sky surveys. The lack of observed velocity offsets in the SDSS quasar catalog is due in part to selection effects, but provides tentative evidence that spin alignment may play a role in reducing recoil velocities. Nonetheless, spin alignment does *not* eliminate the possibility of detecting recoils, unless spins are always aligned to within a few degrees. In a physically-motivated model where spins are aligned only in gas-rich mergers, up to hundreds of spatially-offset AGN could be found in all-sky surveys.

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