

# A correlation between star formation rate and average black hole accretion rate in star forming galaxies

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**Abstract.** We present the results of recent studies on the co-evolution of galaxies and the supermassive black holes (SMBHs) using Herschel far-infrared and Chandra X-ray observations in the Boötes survey region. For a sample of star-forming (SF) galaxies, we find a strong correlation between galactic star formation rate and the average SMBH accretion rate in SF galaxies. Recent studies have shown that star formation and AGN accretion are only weakly correlated for individual AGN, but this may be due to the short variability timescale of AGN relative to star formation. Averaging over the full AGN population yields a strong linear correlation between accretion and star formation, consistent with a simple picture in which the growth of SMBHs and their host galaxies are closely linked over galaxy evolution time scales.

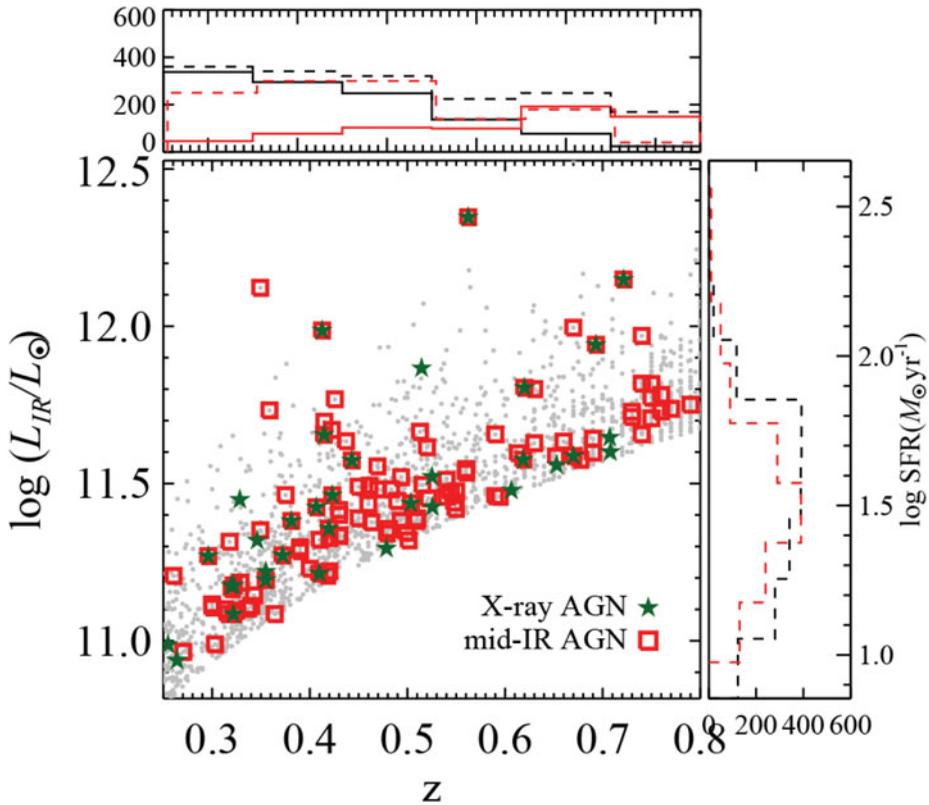
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## 1. Introduction

For the past decades, it has become increasingly clear that the formation of stars in galaxies and the growth of supermassive black holes (SMBHs) might follow parallel evolutionary paths (see Alexander & Hickox 2012, for a review). A number of studies have directly investigated the link between the growth of the galactic stellar mass (star formation rate, SFR) and the growth of SMBH mass (BH accretion rate, BHAR) in galaxies hosting active galactic nuclei (AGN). For high-luminosity AGNs, an increase in the average SFR as a function of BHAR has been observed (e.g. Lutz *et al.* 2008; Serjeant & Hatziminaoglou 2009; Serjeant *et al.* 2010), while other studies have also found weak or inverted connections (Page *et al.* 2012; Harrison *et al.* 2012). Studies with inclusions of lower luminosity AGNs further suggest that the evolutionary link between SMBHs and their host galaxies only exists in high luminosity AGNs that are possibly triggered by mergers, and there is little or no correlation at lower AGN luminosities (e.g. Shao *et al.* 2010; Rosario *et al.* 2012; Rovilos *et al.* 2012). On the contrary, the studies of the *average* BHAR of SF galaxies imply that the galaxy and SMBH growth rates may be strongly connected when averaging over the whole population of SF galaxies (Rafferty *et al.* 2011; Mullaney *et al.* 2012a). Thus, whether BH growth follows SF in all galaxies, or only in the most powerful systems, remains a matter of debate.

The apparent contradictory results may be attributed to the difference in the characteristic timescales of SF and BH accretion. Both theoretical and observational studies have found evidence implying that the SMBH accretion rate can vary by several orders of magnitudes in a time scale much shorter than the typical time scale for galactic star formation events (see Hickox *et al.* 2013, and reference therein). Therefore, to uncover the relation between the SFR and BHAR, the key quantity to study may therefore be



**Figure 1.** The distribution of redshifts and  $L_{\text{IR}}$  for our sample SF galaxies. X-ray AGNs are marked as green stars and mid-IR AGNs are marked as red squares. The histograms in redshift and  $L_{\text{IR}}$  are also shown in the top and right panels. In the top panel, we show the different redshift distributions of the sources with only photometric redshifts (solid red line) and the sources with only spectroscopic redshifts (solid black line). The redshift distributions of AGNs (red dashed line, normalized to scale) and SF galaxies are also shown. In the right panel, we show that AGNs (red dashed line) and SF galaxies (black dashed line) have similar distributions in  $L_{\text{IR}}$  (the histogram of AGNs is normalized to scale). These distributions show that the galaxies with identified AGN in our sample have distributions in redshift and  $L_{\text{IR}}$  similar to those of SF galaxies. Figure adapted from Chen *et al.* (2013).

the *average* AGN luminosity of a population, which thus smoothes over the variations of individual sources. Here we present a study investigating the average BHAR in SF galaxies for a sample in the Boötes survey region (Chen *et al.* 2013; Hickox *et al.* 2013).

## 2. Sample

We use data from the 9 deg<sup>2</sup> Boötes multiwavelength survey, which is covered by the optical photometry observations from NOAO Deep Wide Field Survey (Jannuzi & Dey 1999), optical spectroscopy from the AGN and Galaxy Evolution Survey (AGES Kochanek *et al.* 2012), X-ray data from the *Chandra* XBoötesSurvey (Murray *et al.* 2005), mid-IR data from *Spitzer* IRAC Shallow Survey (ISS, Eisenhardt *et al.* 2004), *Spitzer* Deep Wide Field Survey (SDWFS, Ashby *et al.* 2009) and MIPS 24  $\mu\text{m}$  observations, and far-IR data from the *Herschel* HerMES survey (Oliver *et al.* 2012). The redshifts of our sample come from the AGES survey (spectroscopic) as well as ISS and SDWFS

(photometric, Brodwin *et al.* 2006). Our sample is composed of SF galaxies selected using both the 250  $\mu\text{m}$  *Herschel* SPIRE observations and the 24  $\mu\text{m}$  *Spitzer* MIPS observations.

### 3. Results

We first derive the SFR for our SF galaxies by extrapolating the 250  $\mu\text{m}$  flux measurements to the 8 – 1000  $\mu\text{m}$  bolometric infrared luminosity ( $L_{\text{IR}}$ ) using the SF galaxy templates from Kirkpatrick *et al.* (2012). Since the bulk of  $L_{\text{IR}}$  comes from the cold dust in SF galaxies, and the distribution of dust temperature in SF galaxies has reasonably small scatter, we first derive the total  $L_{\text{IR}}$  for every galaxy in our sample using the ratio between the observed-frame monochromatic 250  $\mu\text{m}$  flux to the total  $L_{\text{IR}}$  derived from the Kirkpatrick *et al.* (2012) template. We next convert the  $L_{\text{IR}}$  to SFR using a Kennicutt relation adjusted to a Chabrier IMF. The redshift and SFR distribution of our sample is shown in Fig. 1. We refer the detailed discussion of SFR estimation of our sample to §2.5 in Chen *et al.* (2013).

To determine the connection between the SF activity and the *average* SMBH accretion rate, we measure AGN luminosities using a combination of X-ray and mid-IR observations. In detail, we convert the mid-IR or X-ray luminosity for individually detected, X-ray (with  $L_X$  (2-10keV)  $> 10^{42} \text{ergs}^{-1}$ ) or mid-IR selected AGNs (Stern *et al.* 2005) using the average bolometric correction factor from Vasudevan & Fabian (2007) and a radiative efficiency of 0.1. For SF galaxies without direct identified AGN, we measure their average X-ray luminosity and BHAR using an X-ray stacking analysis in bins of their SFR (Hickox *et al.* 2007).

We next measure the average BHAR for our entire sample by averaging the  $L_X$  for the detected AGN and the remaining SF galaxies in bins of SFR. We find an almost linear relation between SFR and BHAR:

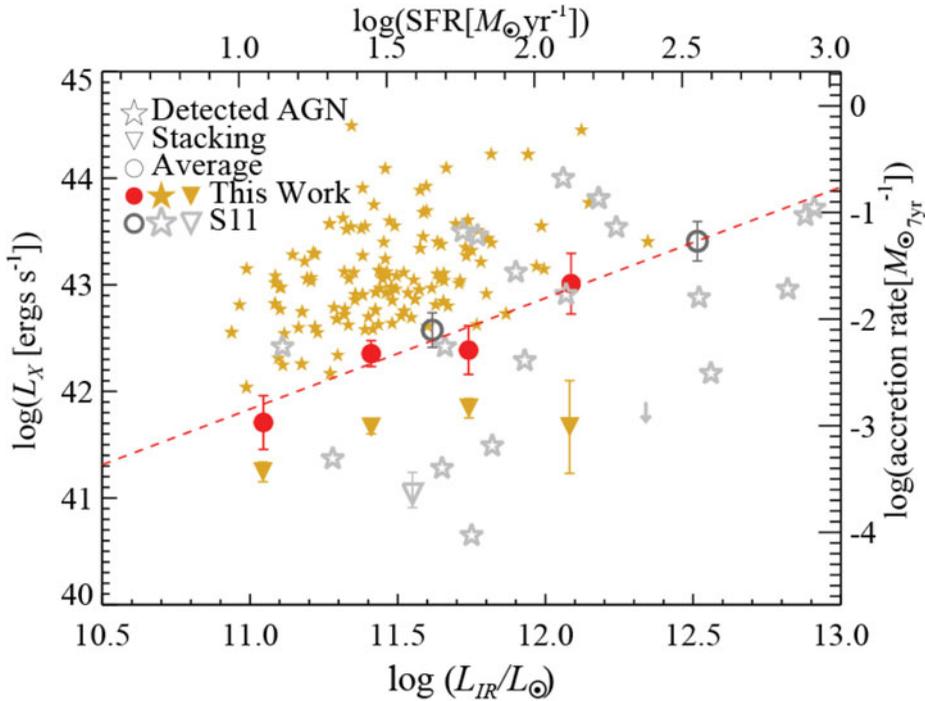
$$\log(L_X[\text{ergs}^{-1}]) = (30.37 \pm 3.80) + (1.05 \pm 0.33) \log(L_{\text{IR}}/L_{\odot}). \quad (3.1)$$

We tested the effect of the flux limits to the observed SFR-BHAR correlation using a mock catalog of galaxies with the flux limits similar to our sample. We found that for a mock catalog of galaxies without intrinsic SFR-BHAR correlation, the observed correlation in the flux limits similar to our real sample is much weaker than the relation observed in Eq. (1). In addition, the observed evolution of  $L_x$  as a function of the average redshift in the different bins of our sample is at least 1.0 dex larger than the pure redshift evolution of the X-ray luminosity function, indicating that most, if not all, of our observed trend is due to the intrinsic correlation between SFR and BHAR.

We also compared our result with the sample of *Herschel* selected SF galaxies in the pencil-beam *Chandra* Deep Field-North (Symeonidis *et al.* 2011) at redshift  $z \sim 1$ . Since Symeonidis *et al.* (2011) measured the  $L_{\text{IR}}$  and  $L_x$  for both detected AGN and normal SF galaxies separately, we could make a direct comparison of the SFR-average BHAR correlation by calculating the average BHAR for their sample using the same methods that we used to derive our average BHAR. The results are displayed in Fig. 2, which show the presence of a correlation between SFR and average BHAR in samples of SF galaxies for a range of redshifts and X-ray flux limits.

### 4. Conclusion

In summary, we studied the average BHAR from a sample of SF galaxies with SFR measurements using *Herschel*. We selected AGNs at X-ray and mid-IR wavelengths to ensure that our BHAR is not biased by AGN obscuration, and employed an X-ray stacking



**Figure 2.** Here we present the SFR-average BHAR relation for far-IR selected SF galaxies (circles) from the 9 deg<sup>2</sup> Boötes field and the pencil-beam CDFN (Symeonidis *et al.* 2011). Also plotted are individually detected AGNs (stars) and the average BHAR from X-ray stacking analysis for normal SF galaxies without direct AGN detections. This figure shows that the *average* BHAR is strongly correlated with the SFR in all rapidly star-forming galaxies; and even though the correlation between the  $L_X$  and  $L_{IR}$  for identified AGNs varies with the depth of the observations, the *average* correlation is consistent. Figure adapted from Chen *et al.* (2013).

analysis to measure SMBH accretion for SF galaxies without direct X-ray or mid-IR identifications. We obtained an almost linear relation between the average BHAR and SFR of  $\log \text{BHAR} = (-3.72 \pm 0.52) + (1.05 \pm 0.33) \log \text{SFR}$ , and determined that this relation also holds for deeper, narrower observations, suggesting that the average BHAR to SFR correlation is a universal consequence of the coevolution between SMBHs and galaxies. The next step of understanding the SFR to BHAR correlation in different populations of galaxies requires information on the *distribution* of AGN X-ray luminosity as a function of SFR, which provides motivation for wide, deep X-ray surveys in multiwavelength fields.

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