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OBSERVATIONAL EVIDENCE FOR UNDERSTANDING THE GROWTH OF SUPERMASSIVE BLACK HOLES

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Abstract. Supermassive black holes are found in the centres of all massive galaxies, but how they are formed and evolve are still largely unknown. They may be formed from seed black holes of ∼100-100000 $M_\odot$ and then undergo mergers and accretion to reach the high masses that we observe today, however, the formation mechanism and thus the mass of the seeds are still unconstrained, as are the rate of accretion and the role of mergers. The *Laser Interferometer Space Antenna* (LISA) will detect gravitational waves emitted by both merging massive black holes and tidal disruption events, and these observations will provide information about the masses and the redshifts of the black holes. The next generation X-ray observatory, *Athena*, is expected to be launched at a similar time to *LISA* and it will provide complementary information such as accretion rates and details about the environment in which these events occur. Here I will present electromagnetic signatures of tidal disruption events and massive black hole mergers and discuss future synergies of *LISA* and *Athena* to better understand these types of events and thus better understand the growth of supermassive black holes.

Keywords: Galaxies: nuclei, quasars: supermassive black holes, X-rays: galaxies, Accretion, accretion disks, Gravitational waves,

1 Introduction

Today we know of many supermassive (∼10^{6-10} $M_\odot$) black holes (SMBH) present in the cores of massive galaxies. However, it is still not clear how they form, nor how they evolve. It is unlikely that the whole population of SMBH form from stellar mass black holes ($\sim 3 - 100 M_\odot$), as even accreting continuously at or above the Eddington limit (the maximum rate for material to be accreted onto the black hole supposing spherical accretion), it is difficult to reach the high masses observed early in the Universe i.e. ∼10^9 $M_\odot$ at z∼7.1 (Mortlock et al. 2011) or 8×10^8 $M_\odot$ at z=7.54 (0.69 Gyr, Bañados et al. 2018). One possibility is that they form from lower mass black holes, known as seed black holes, or intermediate mass black holes (IMBH, 10^{2-5} $M_\odot$), but the observational evidence for IMBH has to date been week. Accretion above the Eddington limit may be possible, thus allowing SMBH to form more quickly, but the physical mechanism is still unclear. Alternatively, mergers may have played an important role in the formation of SMBH, but at what epoch and to what extent is also unclear (e.g. Greene et al. 2020; Mezcua 2017; Volonteri 2012). All three mechanisms may be important. Observations can help discern between the different possibilities and the epochs at which they were thought to be important.

The masses of the seed black holes could range from stellar mass to the most massive IMBH. Whilst the observational evidence for the existence of stellar mass black holes is strong, it is much weaker for the IMBH. Further, how IMBH form and grow are also still open questions (e.g. Miller & Colbert 2004; Greene et al. 2020). They may be formed at the end of the lives of some of the massive, low metallicity population III stars that existed in the early Universe (Fryer et al. 2001). These would give rise to IMBH with masses of the order a 100 $M_\odot$, however, Fryer & Heger (2011) proposed that population III stars could have been as massive as ∼10^{4-5} $M_\odot$ and may have ended their lives as intermediate mass black holes of a similar mass. Alternatively, the earliest, low metallicity dust clouds could directly collapse to form more massive IMBH of ∼10^4 $M_\odot$ (e.g. Loeb & Rasio 1994). Another possibility occurs later in the Universe when dense stellar systems

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evolve and the remnants become centrally concentrated before merging to form IMBH (e.g. Ebisuzaki et al. 2001). Observations of the early Universe will enable us to determine the masses of the seeds. However, these observations are difficult to achieve with current observatories, as the luminosity due to accretion is too faint to detect and current gravitational wave detectors such as *LIGO*, *Virgo* and *Kagra* are currently able to detect stellar mass compact object mergers in the local Universe only. Therefore observations of *local* IMBH have been used to infer the initial masses by comparing them to theoretical predictions of black hole evolution (e.g. Greene 2012; Greene et al. 2020), but due to the detection of few IMBH and poor constraints on their masses, limited results have been obtained.

In order to make headway in understanding the origin and growth of SMBH, it is clear that we need to make constraints on the masses of the seed black holes and when they formed. We need to identify the accretion rate over time and understand the physics behind super-Eddington accretion, and we need to identify if and when mergers were important. This implies the use of both electromagnetic and gravitational wave data. As the mass of the central massive black hole in a galaxy scales with galaxy mass (e.g. Ferrarese & Merritt 2000; Gültekin et al. 2009), searching for IMBH in low mass galaxies is a good way to locate candidates, as black holes are often accreting at low rates and thus are difficult to detect. However, the presence of the galaxy acts as a tracer, making them easier to locate. The mass can then be determined using optical observations, through velocity dispersion relations or similar mass-luminosity relations (e.g. Graham & Scott 2013). To overcome the problem of the black hole being faint and difficult to detect, it is possible to wait until it tidally disrupts a passing star. As the star disrupts, approximately half of the matter falls on to the massive black hole (Rees 1988), causing the system to become brighter by several decades in luminosity in X-rays and at other wavelengths before it decays back to the original luminosity over years, e.g. Holoien et al. (2014); Blagorodnova et al. (2017); Cenko et al. (2012); Lin et al. (2011). These tidal disruption events (TDEs) can also undergo periods of super-Eddington accretion (e.g. Lin et al. 2017, 2022), which can be studied to understand the physical mechanism and constrain accretion rates. Instead, if the black hole is accreting at a lower level, using radio and X-ray observations and the black hole fundamental plane (Merloni et al. 2003; Falcke et al. 2004; Plotkin et al. 2012) can give mass constraints. Better still is to use several scaling relationships to provide robust results (e.g. Koliopanos et al. 2017). Alternatively, data mining in wide-field sky surveys and applying dedicated analysis to archival and follow-up optical spectra can provide many new good candidates (Chilingarian et al. 2018).

However, future gravitational wave facilities, such as *LISA* will also be able to detect IMBH mergers out to very high redshifts (Barausse et al. 2015), and allow us to make constraints on their masses. Indeed, *LISA* will be the ideal instrument to constrain the importance of black hole mergers over cosmic time in the formation and growth of SMBH. However, *LISA* is expected to be launched in the mid-2030's. In order to make headway over the next fifteen years, electromagnetic evidence for ongoing mergers can provide important constraints on the importance of mergers in the growth of supermassive black hole. Locating and constraining the nature of these sources before the launch of *LISA* will help improve future gravitational wave detections.

2 Identifying massive black hole mergers through electromagnetic observations

In order to find previously unidentified mergers we investigated two approaches. The first was to study emission from known mergers and search for sources with similar emission. To date a number of ongoing mergers have been identified through electromagnetic observations. Many have been detected in the X-ray domain. We studied three binary massive black holes where the separation was < 1 kpc. These were: NGC 7727 located at 27.4 Mpc, where the two black holes have masses $M_1 \sim 1.54 \times 10^8$ $M_\odot$ and $M_2 \sim 6.33 \times 10^6$ $M_\odot$ (Voggel et al. 2022); OJ 287 a very well studied binary black hole system located at 1.3 Gpc, where the two black holes are separated by 0.056 pc (Lehto & Valtonen 1996) and their masses are $M_1 \sim 1.8 \times 10^{10}$ $M_\odot$ and $M_2 \sim 1.5 \times 10^8$ $M_\odot$ (e.g. Komossa et al. 2022); and PKS 2131-021 located at 1.5 Gpc with a separation of 0.01-0.001 pc (O'Neill et al. 2022).

We reduced and analysed *XMM-Newton* and *Chandra* data following standard procedure and then extracted and fitted the X-ray spectra of these systems. The best fits were a low temperature black body of $\sim$ 0.1 keV and a hard power law tail with a $\Gamma \sim 1.6$. Good fits ($\chi^2_\nu \sim 1$) were obtained for all spectra. Using these spectral characteristics we determined the hardness ratios expected from the spectral fits and searched the 4XMM-DR11 catalogue (Webb et al. 2020), for similar systems. We retrieved the three sources in our sample and also identified other galaxy pairs, including NGC 7582 (see below) and a dozen new candidates for binary massive black holes. Further work is being carried out to confirm the binary black hole nature and further searches are planned in other X-ray catalogues.

The second approach was to look for modulation of the emission over the long-term. Studies of the aformentioned binary massive black holes, as well as other similar systems have shown (sinusoidal) modulation in the long-term lightcurves, that have been attributed to the orbital motion of the binary black holes. Some systems that appear close to merger have been proposed, e.g. Jiang et al. (2022). OJ 287 also has a well known 12 year modulation in the lightcurve that is indeed attributed to orbital motion (Lehto & Valtonen 1996). In other work, Graham et al. (2015) analysed Catalina real-time survey data of 243500 quasars and found 111 candidate binary SMBH with $<$0.1 pc separation, for example. As the signal is expected to be strongest in the ultra-violet, we exploited the catalogue of 8.86 million detections made with the *Optical Monitor* on board *XMM-Newton* (Page et al. 2012). This catalogue spans 20 years of observations and more than a million objects have been repeatedly observed. We searched for objects that had at least 25 detections in a single filter and searched for sinsoidal modulation in the long-term lightcurve. 441 objects showed a significant ($\chi^2_\nu < 1.3$) modulation on the long term. Identifying these objects we found that 431 were stars/pairs of stars, 4 were X-ray binaries and 6 objects are good candidates for binary massive black holes as they are coincident with galaxies. Again, follow-up work is ongoing to validate their nature.

Modulation can also be expected in the X-ray, as noted above for the case of OJ 287. Whilst investigating the 12 year period in OJ 287, a second period of 3.7 years was also detected in the long term light curve (0.3-10.0 keV) observed with *Swift*. The period is also detected in the 3-10 keV band, but not in the 0.3-3 keV band, indicating that the origin is in the hard X-ray emission. Whilst further work is required to confirm the period, it is possible that it may be due to precession in the inner regions of the disc, which is thought to be seen face on.

Finally, when observing the X-ray colour image of the galaxy pair NGC 7582, it was clear that one side of the galaxy is red and the other side is blue. To investigate if this is due to the rotation of the galaxy, we analysed the X-ray spectra to search for evidence of radial velocity. We extracted *XMM-Newton* EPIC spectra from the blue and the red side of the galaxy using an ellipse with a semi-minor axis of 8" and a semi-major axis of 16" for the blue side and of 11" and 16" respectively for the red side and measured the radial velocities of the Si XIII line at 1.8 keV and the Fe K_α line at 6.4 keV. The radial velocities extracted suggested that there is indeed rotation detected from the galaxy, but due to the poor spectral resolution of the EPIC cameras, the error bars are large making the result significant at 1σ only. Future observations with the *X-IFU* on *Athena* (Barret et al. 2022) will be ideal to constrain the rotation and perhaps discover similar rotation in other galaxies.

3 Conclusions and outlook

We have shown that merging massive black holes can have very similar X-ray spectra, which encouraged us to use the spectral characteristics as criteria with which to search for similar systems. We searched the 4XMM-DR11 catalogue using the hardness ratios calculated from the spectra which revealed the input sources as well as some new candidates for merging binaries. We also analysed long term optical/UV/X-ray lightcurves to search for sinusoidal modulation to find other merger candidates. Again, whilst many of these long-term variables turned out to be stars, a few appear to be good merger candidates. Further work will be carried out to validate the candidates and these pilot studies will be extended to search other catalogues in a similar way. Future integral field spectroscopic observations with the *Athena*/*X-IFU* may also reveal strong evidence for rotation through radial velocities, that could be indicative of other mergers.

If validated, the new candidates will give insight into the nature of the black holes which merge, their masses, their environment and the redshift when these mergers take place. Systems close to merger will become good *LISA* candidates, which can also be followed up in the X-rays, primarily with high resolution spectroscopy with *Athena*, to understand their environment. Tidal disruption events should also be deteted with *LISA* (e.g. Toscani et al. 2022). TDEs can have strong electromagnetic signatures from the radio to the X-ray and can also be followed up using *Athena* to understand the accretion rates and the physical mechanism behind super-Eddington accretion, to further constrain how supermassive black holes form and grow.

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References

Bañados, E., Venemans, B. P., Mazzucchelli, C., et al. 2018, Nature, 553, 473

Barausse, E., Bellovary, J., Berti, E., et al. 2015, in Journal of Physics Conference Series, Vol. 610, Journal of Physics Conference Series, 012001

Barret, D., Albouys, V., den Herder, J.-W., et al. 2022, arXiv e-prints, arXiv:2208.14562

Blagorodnova, N., Gezari, S., Hung, T., et al. 2017, ApJ, 844, 46

Cenko, S. B., Krimm, H. A., Horesh, A., et al. 2012, ApJ, 753, 77

Chilingarian, I. V., Katkov, I. Y., Zolotukhin, I. Y., et al. 2018, ApJ, 863, 1

Ebisuzaki, T., Makino, J., Tsuru, T. G., et al. 2001, ApJ, 562, L19

Falcke, H., Körding, E., & Markoff, S. 2004, A&A, 414, 895

Ferrarese, L. & Merritt, D. 2000, ApJ, 539, L9

Fryer, C. L. & Heger, A. 2011, Astronomische Nachrichten, 332, 408

Fryer, C. L., Woosley, S. E., & Heger, A. 2001, ApJ, 550, 372

Graham, A. W. & Scott, N. 2013, ApJ, 764, 151

Graham, M. J., Djorgovski, S. G., Stern, D., et al. 2015, MNRAS, 453, 1562

Greene, J. E. 2012, Nature Communications, 3, 1304

Greene, J. E., Strader, J., & Ho, L. C. 2020, ARA&A, 58, 257

Gültekin, K., Richstone, D. O., Gebhardt, K., et al. 2009, ApJ, 698, 198

Holoien, T. W.-S., Prieto, J. L., Bersier, D., et al. 2014, MNRAS, 445, 3263

Jiang, N., Yang, H., Wang, T., et al. 2022, arXiv e-prints, arXiv:2201.11633

Koliopanos, F., Ciambur, B. C., Graham, A. W., et al. 2017, A&A, 601, A20

Komossa, S., Grupe, D., Kraus, A., et al. 2022, MNRAS, 513, 3165

Lehto, H. J. & Valtonen, M. J. 1996, ApJ, 460, 207

Lin, D., Carrasco, E. R., Grupe, D., et al. 2011, ApJ, 738, 52

Lin, D., Godet, O., Webb, N. A., et al. 2022, ApJ, 924, L35

Lin, D., Guillochon, J., Komossa, S., et al. 2017, Nature Astronomy, 1, 0033

Loeb, A. & Rasio, F. A. 1994, ApJ, 432, 52

Merloni, A., Heinz, S., & di Matteo, T. 2003, MNRAS, 345, 1057

Mezcua, M. 2017, International Journal of Modern Physics D, 26, 1730021

Miller, M. C. & Colbert, E. J. M. 2004, International Journal of Modern Physics D, 13, 1

Mortlock, D. J., Warren, S. J., Venemans, B. P., et al. 2011, Nature, 474, 616

O'Neill, S., Kiehlmann, S., Readhead, A. C. S., et al. 2022, ApJ, 926, L35

Page, M. J., Brindle, C., Talavera, A., et al. 2012, MNRAS, 426, 903

Plotkin, R. M., Markoff, S., Kelly, B. C., Körding, E., & Anderson, S. F. 2012, MNRAS, 419, 267

Rees, M. J. 1988, Nature, 333, 523

Toscani, M., Lodato, G., Price, D. J., & Liptai, D. 2022, MNRAS, 510, 992

Voggel, K. T., Seth, A. C., Baumgardt, H., et al. 2022, A&A, 658, A152

Volonteri, M. 2012, Science, 337, 544

Webb, N. A., Coriat, M., Traulsen, I., et al. 2020, A&A, 641, A136