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THE GROWTH OF SUPERMASSIVE BLACK HOLES

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Abstract. Supermassive black holes (10^{6-10} M$_\odot$) are found in the centres of galaxies and appear to have a strong influence over the evolution of their hosts. However, it is not yet clear how these black holes form, nor how they evolve. It is thought that supermassive black holes could form from intermediate mass black holes (10^{2-5} M$_\odot$), but few have been identified observationally. Finding and studying intermediate mass black holes would help us understand how supermassive black holes form and evolve. In this work I will discuss some of the recent observational evidence for intermediate mass black holes and discuss their modes of accretion, as well as methods for searching for a significant population, in order to understand how supermassive black holes grow.

Keywords: Black hole physics, Galaxy: evolution, Galaxies: dwarf, Accretion, accretion disks

1 Introduction

Supermassive ($\sim10^{6-10}$ M$_\odot$) black holes (e.g. Lynden-Bell 1969) like Sgr A* are present in the cores of massive galaxies. These black holes appear to play a major role in the life of the galaxy as the mass of the central black hole has been shown to scale with the galaxy mass (Ferrarese & Merritt 2000; Gültekin et al. 2009). This being said, it is still not clear how supermassive black holes form, nor how they evolve. To understand the relationship with the galaxy mass and understand the role they play in the evolution of galaxies, it is essential to comprehend the origin and growth of supermassive black holes.

It is unlikely that supermassive black holes form from stellar mass black holes, as even continuously accreting at the Eddington limit (the maximum rate for material to be accreted onto the black hole supposing spherical accretion), it is difficult to reach masses as high as $\sim10^9$ M$_\odot$ observed in a massive quasar at z$\sim$7.1 (Mortlock et al. 2011) or the 8×10^8 M$_\odot$ black hole found at z=7.54 (0.69 Gyr, Bañados et al. 2018). There are several theories that discuss how supermassive black holes form. They may form from lower mass black holes, namely intermediate mass black holes (IMBH, 10^{2-5} M$_\odot$), but few of these kinds of objects have been found, making it difficult to validate such theories. There may also be a mechanism to accrete above the Eddington limit, thus allowing supermassive black holes to form more quickly (either from stellar mass or intermediate mass black holes), but the physical mechanism is still unclear. Black hole mergers may also contribute to achieving the masses of the supermassive black holes, or accretion plus mergers may be responsible (see Volonteri 2012; Greene 2012; Mezcua 2017, for reviews). In order to determine which is the true mechanism, it is necessary to find a population of intermediate mass black holes and determine where they are found and how they accrete, and/or determine the mechanism for prolonged super-Eddington accretion.

Finding IMBH is difficult. Originally, Ultra Luminous X-ray (ULX) sources were believed to be the best IMBH candidates (e.g. Makishama et al. 2000). ULXs are bright X-ray sources found outside the nucleus of galaxies, i.e. they are not the SMBHs in the galaxy centres. These sources have luminosities that exceed the Eddington limit for a stellar mass black hole ($\sim10^{39}$ erg s^{-1}), which is why it was originally thought that the black hole masses may be greater than those for stellar mass black holes, i.e. IMBH. However, observing ULXs for the last 30 years has provided evidence that most contain accreting stellar mass black holes or neutron stars (Bachetti et al. 2014, and references therein). Only the very brightest (Lx $> 10^{41}$ erg s^{-1}), known as the hyper luminous X-ray sources, are thought to be IMBH candidates.

However, IMBH are unlikely to be in a configuration where they accrete at high rates, meaning that they are intrinsically faint and thus difficult to find. As the mass of the central black hole has been shown to scale

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with the galaxy mass, they should reside in the lower mass galaxies, so many surveys have focussed on them, but few valid IMBH have been found (see Baldassare et al. 2015, and references therein). IMBH have also been proposed to exist in the centres of globular clusters (e.g. Hut et al. 1992), but so far none have been detected in Galactic globular clusters, although stellar mass black holes have now been discovered in these systems (Strader et al. 2012; Tremou et al. 2018).

To overcome the problem of the sources being faint and difficult to detect, it is possible to wait until they tidally disrupt 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 go periods of super-Eddington accretion, making them interesting to study to help understand the formation of supermassive black holes. Rates of tidal disruptions are estimated to be $1.7\pm^{+2.85}_{-1.27} \times 10^{-4}$ gal^{-1} yr^{-1} (90% confidence, Hung et al. 2018). Given the number of galaxies known and the fact that the number density of lower mass galaxies dominates over that of the more massive galaxies (see e.g. Torrey et al. 2015), many tidal disruptions should be happening, including those around IMBH. The number of tidal disruption events is even larger for merging galaxies (Arcavi et al. 2014), so searching in the centres of galaxy clusters where minor galaxies frequently merge with major galaxies can enhance the chances of identifying TDEs and thus IMBH.

As both hyperluminous X-ray sources and TDEs are bright in X-ray and it is necessary to survey a large region of sky to identify a new population of IMBH (as described above), the ideal place to search is in X-ray catalogues. *XMM-Newton* is the *European Space Agency's* second cornerstone mission from the *Horizon 2000 programme* (Jansen et al. 2001) and it has the largest effective area of any X-ray satellite (Longinotti 2014), thanks to its three X-ray telescopes observing in the 0.2-12.0 keV domain, each with $\sim$1500 cm^2 of geometric effective area. The field of view (FOV) is 30' meaning that approximately 100 serendipitous sources are discovered in a reasonable length observation (Watson et al. 2009).

The *XMM-Newton Survey Science Centre*[*] (SSC), a consortium of ten European Institutes (Watson et al. 2001) produces catalogues of detections made with the *EPIC* cameras as well as with the OM. The most recent version of the X-ray catalogue is 3XMM-DR8. It was released in May 2018[†]. It contains 775153 X-ray detections, where objects have been detected as many as 59 times over 17 years from Feb. 2000 to Nov. 2017. 332 columns of information are provided for each detection, including coordinates, observation date, time and mode, exposure and background information, counts, fluxes and rates in 7 energy bands, maximum likelihoods of detection, quality and variability flags, as well as multi-band images, lightcurves and spectra. The catalogue is an excellent resource for a wide variety of astrophysical research such as finding new objects and studying homogeneous populations of objects.

2 Intermediate mass black hole candidates

The best studied hyperluminous X-ray source was found in the *XMM-Newton* catalogue (Farrell et al. 2009). 2XMM J011028.1-460421, more commonly known as Hyper Luminous X-ray source 1 (HLX-1, Godet et al. 2009; Webb et al. 2010) has a mass of $\sim 10^4$ M$_\odot$ (Godet et al. 2012). It is highly variable, where the variability comes from periodic accretion from a companion star in a highly elliptical orbit, which is tidally stripped as it approaches periastron (Lasota et al. 2011; Godet et al. 2014; Webb et al. 2014). It is found at 8" from the centre of the galaxy ESO 243-49, which is in the galaxy cluster Abell 2877 (Santiago & Vale 2008). ESO 243-49 is one of the more massive galaxies in the cluster (Hudson et al. 2001). Given its size and proximity to the host cluster centre, ESO 243-49 is expected to have suffered dynamical effects, such as interactions or accretion of other bodies, thus making it probable that HLX-1 stems from a minor merger with its host (Webb et al. 2010; Mapelli et al. 2012; Webb et al. 2017), although no evidence for a recent merger has been found (Musaeva et al. 2015; Webb et al. 2017). Such a merger could be responsible for placing the companion star to the IMBH in its elliptical orbit. As the time between outbursts is becoming progressively longer, it appears that the orbit is becoming unbound, thus making HLX-1 an exceptional system whose lifetime is only tens of years (no outbursts observed in the early 1990s with *Rosat* Webb et al. 2010). This would explain why it appears to be a unique object.

Many TDEs have been identified through exploring *XMM-Newton* data, (e.g. Lin et al. 2011; Saxton et al.

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[*] `http://xmmssc.irap.omp.eu/`

[†] `http://xmmssc.irap.omp.eu/Catalogue/3XMM-DR8/3XMM_DR8.html`

2015; Lin et al. 2017a; Saxton et al. 2017; Lin et al. 2018). Some of these TDEs show evidence for IMBHs, i.e. the black hole in the centre of the inactive galaxy IC 4765-f01-1504 which underwent a tidal disruption event in 2006. The mass of the black hole has been estimated to be 6×10^4 - 4×10^6 $M_\odot$ (Lin et al. 2011). The massive black hole in a dwarf galaxy orbiting 6dFGS gJ215022.2-055059, also underwent a TDE starting in ∼2005. The mass of this black hole was estimated mass to be $5.3 \times 10^4 < M_{BH} < 1.2 \times 10^5$ $M_\odot$ (Lin et al. 2018). Further a TDE showing super-Eddington accretion over more than 10 years was also discovered (Lin et al. 2017b). This supports the idea that it is possible to fuel supermassive black holes at high rates for long periods, although the physical mechanism remains to be elucidated.

3 Finding new intermediate mass black holes

Taking the average length of an *XMM-Newton* observation, the TDE rate and the fact that a TDE involving an IMBH can be detected out to a redshift of ∼1.5 and taking into account the number of galaxies in the field of view, hundreds of TDEs should have been detected with with *XMM-Newton* (Webb 2019). These have not all been identified as a deep X-ray observation of the field in question must exist for the variability to be identified. In 3XMM-DR8, ∼60 objects have varied by more than a factor of 100 in X-ray. Such variability is typical of TDEs, but the signal to noise of these data are insufficient to conclude on the nature of the X-ray source. If the source could be followed up immediately after such extreme variability is identified, it would be possible to identify new TDEs and have sufficient signal to noise in the spectrum to determine the mass through spectral fitting. *XMM-Newton* is expected to fly for another 10 years and so tens of new TDEs could be identified with rapid follow-up (Webb 2019). Amongst these, new IMBH should be identified.

Other new X-ray observatories will also survey the same region of sky repeatedly, such as *eRosita* (Predehl et al. 2011) and *SVOM* (Space-based multi-band astronomical Variable Objects Monitor Cordier et al. 2015; Götz et al. 2014). These should reveal many new transients and notably TDEs and therefore IMBHs.

Alternatively, searching for IMBH in low mass galaxies remains one of the most likely places to investigate. However, scaling relations are often used to infer the mass of the central black hole and these can have quite large error bars, i.e. the black hole fundamental plane (Merloni et al. 2003; Falcke et al. 2004; Plotkin et al. 2012), the black hole mass versus velocity dispersion relation (e.g. Ferrarese & Merritt 2000; Gültekin et al. 2009) or similar mass-luminosity relations (e.g. Graham & Scott 2013), which can lead to black hole masses that are either under- or over-estimated. One way to overcome this problem is to make several observations of each object and 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).

Many TDEs have been discovered using optical surveys like the Zwicky Transient Facility (Graham et al. 2019) or the All-Sky Automated Survey for Supernovae (ASAS-SN) (e.g. Holoien et al. 2014). The Large Synoptic Survey Telescope (LSST), which will repeatedly survey the same region of sky with excellent sensitivity should therefore discover many more TDEs, which may house IMBHs (Bricman & Gomboc 2018). Moving to other wavelengths, low state/quiescent IMBHs should have steady radio jets. The Square Kilometre Array (SKA) will be able to detect almost any quiescent IMBH in our Galaxy ($\sim \mu$Jy). Plotting the radio fluxes against quasi-contemporary X-ray fluxes (the fundamental plane of black hole accretion) will demonstrate their IMBH nature (Maccarone 2004). Finally, moving away from the electromagnetic spectrum and to gravitational waves, future facilities, such as *LISA* will also be able to detect IMBH (Barausse et al. 2015).

Over the next twenty years, a significant population of IMBH should be identified, helping us to understand how supermassive black holes form and evolve and therefore shed light on their relationship with their host galaxies.

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