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STELLAR-MASS BLACK HOLES

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1. INTRODUCTION

Stellar-mass black holes are the result of a gravitational collapse of a massive star at the end of its life. The core of such star collapses to singularity – a point of infinite density and space-time curvature – that is cloaked in the event horizon. The gravitational force of the resulting black hole is so strong that no light or signal can escape its event horizon. This essay will address how astronomers search for stellar-mass black holes, will attempt to describe their characteristics, and will also discuss the current knowledge on Milky Way black hole candidates and their companion stars, and the connection between X-ray sources and black holes.

2. STELLAR-MASS BLACK HOLE CHARACTERISTICS

When the stellar core collapses to singularity, the resulting black hole is described by three parameters: mass, angular momentum (spin) and electric charge (Chruściel et al. 2012). Although common definition of a stellar-mass black hole assumes its mass lies within the ∼4–15 solar masses ($M_\odot$) range, and suggested to be clustered around ∼7 $M_\odot$ (Bailyn et al. 1998), discoveries of more massive black holes were made in the recent years, such as the 24–33 $M_\odot$ stellar-mass black hole (Prestwich et al. 2007) in the variable X-ray source IC10 X-1 located in the local group starburst galaxy IC10. Current theoretical studies (Belczynski et al. 2010) extend the upper mass limit of stellar-mass black holes at 30 $M_\odot$ for stars with moderate metallicity and even 80 $M_\odot$ for low, globular cluster-like, metallicity environments. Because black holes have such a strong gravitational force, no light or signal can escape their event horizons, so they cannot be seen and measured directly. The strongest evidence for the existence of stellar-mass black holes comes from X-ray binaries (XRBs) – a class of binary stars with X-ray emission. An XRB system consists of a component called the donor (also referred to as secondary component), and a primary component called the accretor. The accretor captures matter from the secondary component – usually a relatively normal star – releasing large amounts of energy in the process. A specific configuration of XRBs, referred to as black hole binaries (BHBs), contain black hole as their accreting component. As the secondary component star matter falls on the primary component – the black hole – it develops a spiral motion, increases its temperature to millions of degrees K because of the friction and the superheated material produces X-ray emission - see figure 1. By observing the orbit of the visible secondary component, it is possible to determine the lowest bound on the mass of the black hole (Hawking 1996). A large number of BHBs discovered comes from the observation of X-ray transients (XRTs) - episodic outbursts of X-ray emission due to instabilities in the accretion process in a BHB system (Casares & Jonker 2013). XRTs are very bright events on the sky and are easily spotted by X-ray satellites, such as the XMM-Newton and Chandra observatories. Between those XRT outbursts, the BHB system remains in so called quiescent state whereby it is possible to perform radial velocity studies on the secondary component. The very first BHB system discovered – Cygnus X-1 – has a massive, 40±10 $M_\odot$ O9.7Iab star as its secondary component (Wiktorowicz & Matthews 2008), so it is classified as a high-mass XRB system. These high-mass XRBs are young systems with ages less than a million years (Tauris & van den Heuvel 2006). They have secondary components of >10 $M_\odot$ and in the Milky Way these sources are located among the other OB-type stars in the star-forming regions of our galaxy. The most massive known stellar-mass black hole IC10 X-1 has a 35 $M_\odot$ Wolf-Rayet star as the secondary optical component (Silverman & Filippenko 2008). At the present time ∼20 BHBs are confirmed (Remillard & McClintock 2006) and most of them, however, are low-mass XRB systems having K spectral type dwarfs as their secondary components. These low-mass systems have $\lesssim$1 $M_\odot$ companions and are found in the Galactic bulge and in globular clusters (Tauris & van den Heuvel 2006) as they actually belong to the older stellar population.

3. ULTRA-LUMINOUS X-RAY SOURCES

In the range between stellar-mass black holes and supermassive black holes of 10^5–10^9 $M_\odot$ that are found

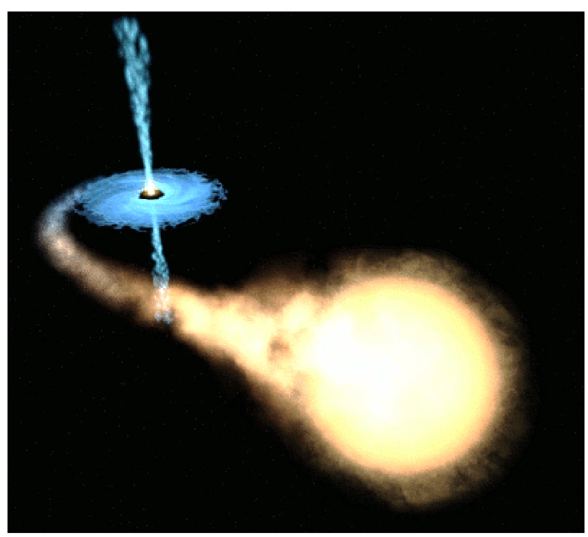

Figure 1. An artist's illustration of matter falling from the companion star into a black hole in a BHB system. X-ray emission is beamed off along the rotational axis of the accretion disk. (A public domain image.)

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in the centers of many galaxies, lies the domain of intermediate-mass black holes that could be related to extragalactic ultra-luminous X-ray sources (ULXs). These black holes are of $\sim 10^2$–10^5 $M_\odot$ (Miller et al. 2004) and have attracted a great deal of observational and theoretical attention. The subject of underlying nature of ULXs is still open for discussion as the amount of data available on these sources is more limited, if compared to stellar-mass black holes. Due to the very high luminosities and distances of ULXs, some views suggest it could be tempting to associate these objects with a specific class of intermediate-mass black holes to explain very high X-ray fluxes, however investigations are suggesting other models may be applicable. Among the options considered are stellar-mass black holes (Fender & Belloni 2012) described earlier, as is with the case of ULXs in Antennae galaxies, whereby the model (King et al. 2001) suggests an XRB system with accretion disk and the most of the X-ray emission being non-isotropic (beamed) and, thus, focused along its rotational poles. For an observer situated near the beaming axis, this model would explain anomalous X-ray fluxes. The discovery of He II emission nebula ionized by the radiation from ULX in the dwarf irregular galaxy Holmberg II (Kaaret et al. 2004) supports the beaming theory. The explanations of ULXs association with intermediate-mass black holes of $\sim 10^2$–10^5 $M_\odot$ seems to become more popular as more ULXs have been identified that are strong intermediate-mass black hole candidates, however it is argued that the existence of the required amount of such massive sources in a galaxy could theoretically be improbable.

4. SEARCHING FOR STELLAR-MASS BLACK HOLES AND MILKY WAY CANDIDATES

Cygnus X-1 has been established as a black hole via so called dynamical observations (Webster & Murdin 1972) whereby radial velocity of HD 226868 – then assumed visible secondary component of an XRB system – was systematically measured on the 98-inch Isaac Newton Telescope from August to October 1971. The periodic Doppler shifts observed appear due to the visible component orbiting the black hole and moving back and forth from the observer. From the application of Kepler's Third Law to these measurements, the mass of the unseen primary component is estimated, and, as with the case of Cygnus X-1, the primary component is found too massive to be a white dwarf or a neutron star and, thus, it is considered a black hole. All the well-studied stellar-mass black holes – fewer than fifty of them so far – have been found within XRB (Fender et al. 2013) systems. Initially it was estimated there are likely as many as 10^8 stellar mass black holes in the Milky Way galaxy (Shapiro & Teukolsky 1983), and a significant stellar-mass black hole population is believed to be located within isolated, non-binary systems that do not reveal themselves via strong X-ray emissions. It is possible that such isolated black holes are actually faint radio sources that should be detectable via proper motion measurements with future highly sensitive instruments, such as the Square Kilometre Array (Aharonian et al. 2013), scheduled for the first light in 2020.

Recent discoveries of a new black hole candidate with significant evidence in M62 (Chomiuk et al. 2013) and two black holes in M22 (Strader et al. 2012) have turned Milky Way globular clusters into new hunting grounds. It is argued that M22 – a massive globular cluster with dense core, located near the galactic bulge region – may contain $\sim$5–100 black holes alone. This represents an important shift in our understanding of black holes as it is now believed they may be common in globular clusters. Those new objects found also provide us with a good opportunity to determine their physical parameters with good accuracy because distances to globular clusters are well-known. The M22-VLA1 and M22-VLA2 objects are identified as black holes using both radio and X-ray spectra. The radio continuum images were obtained on the Karl G. Jansky Very Large Array (VLA) radio telescope and then compared to archived data from the Chandra X-ray Observatory. There is a specific correlation between the 8.4 GHz radio luminosity and 3-9 keV X-ray luminosity $L_R \propto {L_X}^{0.58}$ for black holes that differentiates them from white dwarfs and neutron stars (Gallo et al. 2006) – please refer to figure 2 on the last page. Such a correlation has been observed to be strongly maintained (Corbel et al. 2013) throughout multiple decades of X-ray and radio observations for a number of objects. This means there should be a connection between the accretion flow and radio jets. The exact mechanism of this connection is still yet to be understood. A number of different models are being currently developed to explain this phenomenon. For example, it is suggested that radio emission may come from radio jets that originate in the inner regions of the accretion flow (Yuan & Cui 2005) – in a so called accretion-jet model. The M62-VLA1 has been discovered with the same X-ray-radio correlation technique and instruments.

5. CONCLUSIONS

Black holes are among the most enigmatic objects in our universe. Not only our laws of physics break down at singularities they conceal, black holes are unique testbeds for General Theory of Relativity and other advanced theories in cosmology and quantum physics. For example, some suggest that the dark matter could be made of primordial black holes (Frampton et al. 2010) or that black holes constitute all of the dark matter (Frampton 2011). Theoretical estimations of stellar-mass black holes provide us with an insight that there are many more yet to be found. Many candidates are being discovered within the Milky Way and also nearby galaxies, such as the 50 candidates recently identified in the M31 Andromeda Galaxy (Barnard et al. 2014). It looks like the key to get more discoveries would be the future, more sensitive instruments, such as the Square Kilometre Array, including wide-field radio surveys that would target isolated stellar-mass black holes with faint radio continuum emission.

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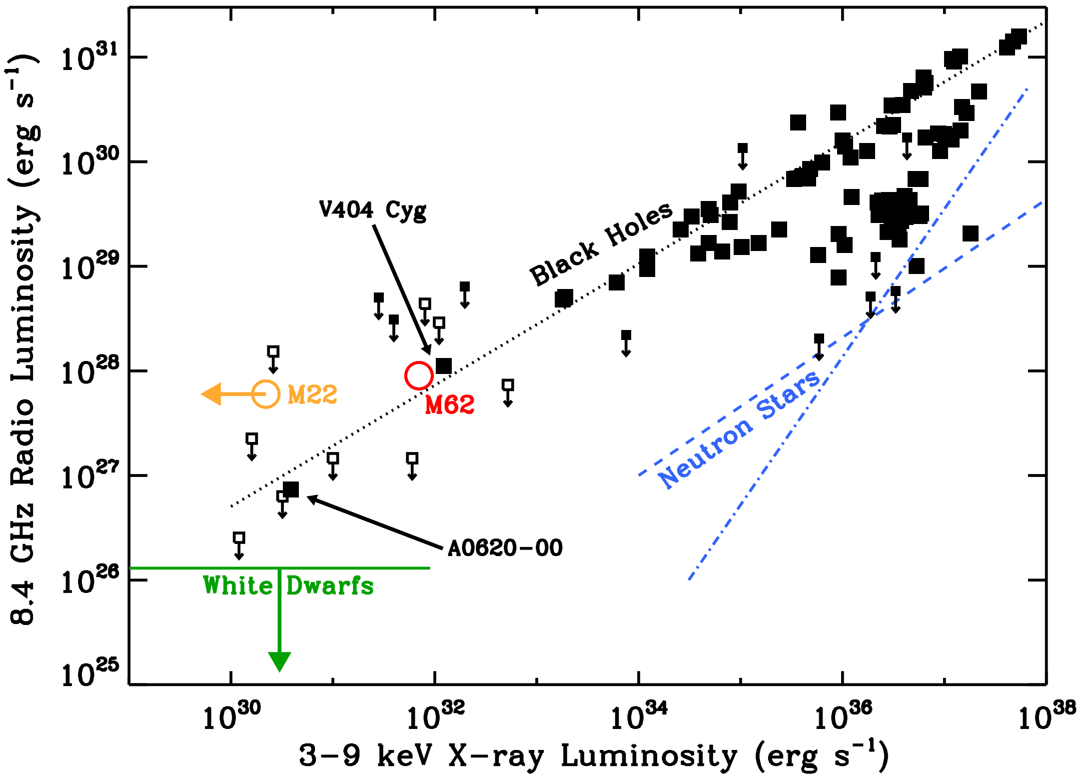

Figure 2. The X-ray-radio correlation for stellar-mass black holes, chart from Chomiuk et al. (2013). Filled squares have simultaneous X-ray and radio observations, empty squares are non-simultaneous. Black dotted line corresponds to the $L_R \propto {L_X}^{0.58}$ correlation. Objects discovered in M22 and M62 as well as V404 Cyg – arguably the most solid case of stellar-mass black hole in our galaxy – are shown.

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