

Black Holes in Our Universe

Do They Inch Up the Mass Ladder?

Prajval Shastri

Current technologies have enabled glimpses at the many facets of black holes, which we know to be plentiful in our cosmos. A panoramic view of the evidence for them is presented here across the large range of masses that they span.

Introduction

Black holes are bits of space, or more precisely, ‘space-time’, from which even light cannot escape, because they are regions of extremely strong gravity. We now know that black holes, especially those that are a million times heavier than our Sun or more, *i.e.*, ‘supermassive’, are abundant in our universe, occurring in the centre of our Milky Way and in the umpteen galaxies around us. A black hole must indeed be ‘black’ – so then, how do we know that they exist? What are their masses? How do they form and grow? We will explore these questions with a broad brush, framed by results from the state-of-the-art telescopes that are humanity’s high-technology windows onto the universe. For reasons that will become clear in what follows, we will use the unit for the mass of black holes that astrophysicists use in their technical discussions, which is M_{\odot} , the mass of our sun, or ‘solar mass’, and $1 M_{\odot}$ is approximately 2×10^{30} kg.

1. The Early Flashes

As early as in 1783, John Mitchell conjectured that there may be objects massive enough that even light would not escape from them, which by implication would be ‘black’. Karl Schwarzschild predicted the existence of black holes using Einstein’s theory of General Relativity. Moving to the astrophysical context,



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Keywords

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¹Of the Manhattan Project fame.

Oppenheimer¹ and Volkoff predicted in 1939 that stars above a certain mass would collapse [23], and John Wheeler coined the term ‘black hole’. Little was it imagined that not long after, our skies would reveal an abundance of real objects predicted by these theoretical arguments.

2. The Smallest Known

The smallest black holes that we know are a few M_{\odot} . Really tiny black holes have been hypothesised (*e.g.*, of the size of an electron, [5,1] but not yet substantiated by experiment. I will not discuss them, but the reader should delve into these fascinating ideas using the readings.

The earliest evidence for stellar black holes came from the opening of the X-ray window onto our Milky Way. The first candidate was discovered in the constellation Cygnus; a bright X-ray emitter associated with a twin-star system, and christened Cygnus X-1. It has a massive star and a black hole orbiting each other. With an optical telescope it is the companion star of the black hole which is visible, which produces stellar winds blowing away from it. Some of the matter from this wind is pulled by the black hole onto itself. The matter thus spirals into the black hole to form an ‘accretion disc’, which heats up in the process to temperatures far hotter than in our Sun, and therefore shines brightly in X-rays. This is how Cygnus X-1 was spotted.

Indeed it is this type of accretion disc around the fictional black hole *Gargantua* that mesmerised us in Christopher Nolan’s film *Interstellar*. The physics-wise correct rendering by the computer code used in the film (DOUBLE NEGATIVE GRAVITATIONAL RENDERER) is in Figure 15 of the research paper that resulted from the film [17].

How do we know that the dark companion is a black hole from which no light can escape? The evidence comes from what astrophysicists call ‘dynamical arguments’. The two stars are gravitationally bound. The velocity of the visible star can be measured from the Doppler shifts of its spectral lines. If the orbital period is also measured, then the size of its orbit can be computed. The

The discovery of gravitational waves was a phenomenally robust confirmation of Einstein’s theory of General relativity; the measured distortion was smaller than a thousandth of a proton diameter, making it the most sensitive scientific instrument ever built; and it was the first direct measurement of ripples in our space-time.



total mass follows from Kepler's laws. Further, the mass of the visible star can be inferred from the type of optical spectrum it has. Therefore, the mass of its 'dark' companion, *i.e.*, the putative black hole can also be inferred.

The case for a black hole in Cygnus X-1 was strong enough to lead black-belt black hole physicists Kip Thorne and Steven Hawking to make a bet (for and against the black hole hypothesis respectively [12]). The evidence quickly grew stronger. There was no looking back when the masses of dark companions of stars in twin-systems or binaries came out to be in excess of $5M_{\odot}$, which could only be black holes – because our theoretical understanding [23, 4, 7] tells us that if a star has that much mass, its own gravity will drive it to collapse into a black hole. Indeed, in 2007, in Messier33, the farthest galaxy that could possibly be seen by naked eye (under exceptionally dark skies and with sharp vision), a black hole of mass $16M_{\odot}$ was reported [8, 24]. ([8] contains an artist's rendition of the stellar wind from a massive star accreting onto a companion black hole.) About 20 black holes with masses determined by the dynamical method have been discovered in our Milky way to date, listed in the on-line catalogue BLACKCAT [10]. Needless to add, Hawking conceded the bet to Thorne [12].

Most definitive of all, however was the spectacular discovery of gravitational waves from the merging black holes GW150914 [3,6] and GW151226 by the Laser Interferometer Gravitational-wave Observatory² (LIGO) [19]. The discovery of GW150914 was spectacular for multiple reasons (see box with three).

Relevant to our story, though, is the fact that LIGO was able to measure the masses of the merging black holes: 29 and $36 M_{\odot}$ in GW150914, and 14 and $8 M_{\odot}$ in GW151226, thus affirming beyond doubt, the existence of stellar mass black holes.

How do these black holes form? Black holes are theoretically predicted to be the natural consequence of the death of massive stars (about $20 M_{\odot}$ or more). The broad consensus is that the most massive that a star can be is about $150 M_{\odot}$, and there have been claims that even heavier ones exist [14]. When these stars run out

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²Biman Nath, Gravitational Waves: A New Astronomical Tool and Tarun Souradeep, LIGO-India: An Indian Mega-project for Gravitational-Wave Science, *Resonance*, Vol.21, No.3, 2016.



of nuclear fuel (see article by Hasan in this issue), they can no longer generate heat and therefore pressure to balance their own gravity. The stand-off between the pressure from nuclear burning and the star's own gravity thus ends, and the star collapses. If its mass is larger than about $20M_{\odot}$ it undergoes a supernova explosion, expelling a lot of the mass, but leaving behind a black hole that is at least $5M_{\odot}$. While this has been considered to be the norm, there have been predictions that stars of the highest masses may not explode but might instead directly collapse into a black hole, and indeed such a phenomenon may explain the disappearance of a star in the galaxy N6946 [21]. The collapse of stars into black holes might account for some of the extraordinarily powerful flashes of gamma-ray light detected about once a day (gamma-ray bursts, *e.g.*, [11]), that we would see lighting up the whole sky if we had gamma-ray eyes.

3. Next Up: Intermediate Mass Black Holes?

A fascinating fact about black holes is the mass gap: while known black holes under mass $100M_{\odot}$ currently number about 20, and those of masses over a million M_{\odot} are known in their thousands (we will get there yet!), evidence for black holes of masses in between these limits is annoyingly scarce! Such black holes with masses broadly between 1000 and $100000M_{\odot}$, are referred to as intermediate-mass black holes (IMBHs).

One set of candidates that could be IMBHs are point-like highly luminous X-ray emitters in galaxies outside the Milky Way, which are located away from the centres of those galaxies – referred to as Ultraluminous X-ray Sources. Given their large X-ray power, it has been tempting to posit that they are accreting black holes (of the kind described in the previous sections) but of much higher masses, *i.e.*, IMBHs. However, no confirmation of such masses using dynamical arguments has been made so far, *e.g.*, [16], and so the question of whether they are IMBHs is at best, unsettled.

Tenacious searches for IMBHs in the centres of ‘dwarf’ galaxies (*i.e.*, galaxies much smaller than our Milky Way, and similar



to the Large Magellanic Cloud) have yielded several black holes with masses less than that of the black hole in the centre of our Milky Way [26,25,& refs therein]. Thus the mass gap has begun to fill from the high end. The evidence that these discoveries are indeed black holes comes from gas dynamics – the light from the accreting matter around these black holes lights up the gas clouds in the vicinity, which therefore emit atomic emission lines, which in turn contain imprints of their Keplerian orbital speeds driven by the central black hole. Thus several of these black holes have measurements that are securely in the range 10^5 - $10^6 M_{\odot}$.

But the mass gap may yet close! 47 Tucanae, a globular cluster (gravitationally bound old ‘sibling’ stars) in the Milky Way that has long enchanted watchers of the southern skies, has finally revealed an IMBH from dynamical methods [15, 18]. Hopes had long been pinned on it. The ambiguity has ended with dynamical arguments based on the movement of its pulsars, giving the mass of the central black hole, of about $2000 M_{\odot}$, right within the gap.

4. The Top of the Mass Ladder: Supermassive Black Holes

Our Milky Way harbours a supermassive black hole (SMBH) in its very centre [20]. The dynamics of stars orbiting it give a mass of 4 million M_{\odot} . Intriguingly, finding evidence for such giant black holes in the universe has been the easiest of all. One of the major achievements of the *Hubble Space Telescope* was to reveal them in the centres of a large number of the familiar galaxies in our cosmic neighbourhood. Indeed the only SMBH we know reside in the centres of galaxies. They can accrete matter too, and then, just like their stellar-mass cousins, they shine and become extremely easy to spot, and indeed they are the most powerful persistent sources of light in the universe that we know – often referred to as active galactic nuclei or quasars. As a consequence, not only have thousands of them been discovered, but they can be seen out to mind-bogglingly large distances, and therefore to very early times in the life of the universe. Furthermore, the accreting matter swirling into these black holes is also able to squirt out

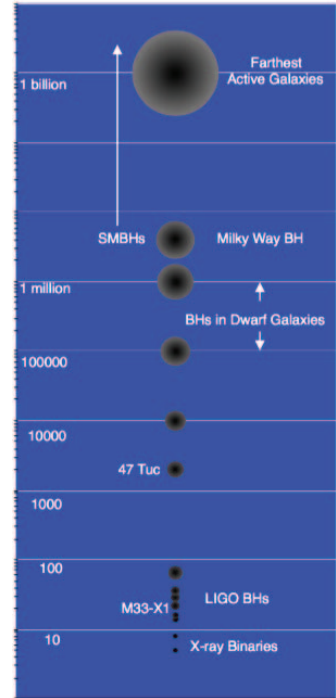


Figure 1. A schematic (not to scale) of the black hole mass ladder. The black hole mass in M_{\odot} is shown on the y-axis, which is a logarithmic scale.





Figure 2. The twin-jets of plasma in Centaurus-A that are squirted out by its supermassive black hole and have expanded into plumes. They are most easily seen at radio frequencies. (Image credit:CSIRO)

powerful jets of plasma that leap out into intergalactic space, creating some of the most enchanting images we know (see *Figure 2*).

How do these giant black holes form? Despite the thousands known, understanding formation is a challenge we are still grappling with. Particularly because, although the prevalence of these giant black holes is highest at Cosmic High Noon, (*i.e.*, 2-3 billion years after the Big Bang, which occurred 13.8 billion years ago), some are seen at a mere few 100 million years since the Big Bang, and they are giants among giants (masses of several billion M_{\odot}) to boot! Assembling such monstrous masses within such a short time since the birth of the universe is a daunting task indeed.

One way to grapple with the challenge theoretically is to posit that much larger black hole seeds than what dying stars leave behind can form in the very early universe, by the direct collapse of an enormous gas cloud into a black hole, [*e.g.*, 22]. This line of investigation is still in its infancy, but dramatic evidence is already emerging, *e.g.*, the discovery of CR7 (abbreviation of COSMOS Redshift 7, a name inspired by the nickname of the famous footballer Cristiano Ronaldo, [13]). It is the most luminous galaxy known from that era of the universe, and its brightest component has only Hydrogen and Helium – the dramatic absence of other atomic lines implies that it predates stellar cooking of the heavier elements. [2] have modeled its detailed history from known physics and concluded that it has all the pre-requisites to make it an accreting directly collapsed black hole [see also 9].

5. Conclusion

So do black holes inch up the mass ladder? Some black holes left behind by the very first dying stars of the universe possibly do, over cosmic history. However, we do need a substantial number of black holes to have a jump start, by directly collapsing from gas clouds into large black hole seeds. This mechanism appears to be the only way that they can build up to a billion solar masses quickly, within a few hundred million years from the beginning



of time – because we already see about eighty of them as shining beacons from the dim mists of cosmic history, and are likely to see many more. Indeed, exciting times lie ahead.

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