215. Black holes and Gaia: an update

There is overwhelming evidence for the existence of black holes. Amongst them, supermassive black holes, with masses upwards of $10^5 M_\odot$, appear to exist at the centres of almost all large galaxies, growing over cosmological time by hierarchical galaxy mergers.

The existence of such objects so soon after the Big Bang, at redshifts $z > 7$ (e.g. Mortlock et al., 2011; Bañados et al., 2018; Wang et al., 2021) suggests that they originated by the seeding from massive star collapse in the early Universe, or perhaps more directly from the collapse of early supermassive stars, or even through the collapse of large gas clouds pre-dating the first stars.

Here, Gaia contributions include (a) the identification of dual active galactic nuclei as a result of galaxy mergers (essay 163), (b) the identification of hypervelocity stars originating from the supermassive black hole in the Galactic centre and elsewhere (essays 22 and 166), and (c) tidal disruption events, resulting from a star passing close to a supermassive black hole such that tidal forces overcome its self-gravity (essay 206).

Intermediate-mass black holes, $10^2 - 10^5 M_\odot$, are also inferred to exist in the centres of galaxies or globular clusters, and a few hundred candidates are known (e.g. Chilingarian et al., 2018). I described these, and Gaia's contribution to the evidence for such an object in the globular cluster M4 (Vitral et al., 2023), in essay 177.

Stellar mass black holes, with masses $5 - 50 M_\odot$ or higher, result from the gravitational collapse of massive stars at the end of their lives. Isolated stellar mass black holes are most directly discoverable from photometric microlensing, or less directly through their dynamical manifestations in open clusters (essay 175), or stellar streams (essay 176).

The only confirmed object is OGLE–2011–BLG–0462 ($7.1 M_\odot$, $d = 1.58$ kpc), characterised from astrometric measurements with HST (Sahu et al., 2022). A recent candidate, from the Gaia science alerts system (essay 202), is Gaia18ajz, at $4.9 M_\odot$ (Howil et al., 2024). Gaia constraints on Spitzer candidates are discussed by Rybicki et al. (2024), with prospects for detecting primordial black holes discussed by Verma & Rentala (2023).

The discovery space is much larger for stellar mass black holes in binaries. In compact systems, they may be identified from the X-ray emission arsing from mass transfer, divided (according to donor mass) into low-mass (LMXB) or high-mass (HMXB) X-ray binaries. There are more than 20 candidates, including Cyg X1 ($M_{\rm bh} \sim 21 M_\odot$ in a 5.6-d period binary) and V404 Cyg ($M_{\rm bh} \sim 12 M_\odot$ in a 6.5-d period binary) both at distances of 2–2.5 kpc. A recent Gaia result suggests that V404 Cyg is part of wide hierarchical triple (Burdge et al., 2024).

Black holes in binaries may also be manifest, photometrically, through the tidal distortion of the envelopes of their companion star, extreme examples of the class of ellipsoidal variables (essay 133). Rimoldini et al. (2023) identified 65 300 candidate ellipsoidal variables in Gaia DR3, and searches for black hole systems amongst them are ongoing (Gomel et al., 2023; Fu et al., 2022; Rowan et al., 2024). Shahaf et al. (2023), for example, identified eight candidate black-hole systems with compact-object masses $\gtrsim 2.4 M_\odot$.

Among other discovery techniques are binary black hole mergers evidenced by gravitational waves, the first of which, GW150914, was detected by LIGO/Virgo in 2015. Efforts to extend Gaia's science alerts trigger limit to $G > 19$ mag, with the goal of detecting their electromagnetic counterparts, are ongoing (Kostrzewa-Rutkowska et al., 2020; Biswas et al., 2023; essay 202).

An important discovery method, and a field now being opened up by Gaia, is the detection of black holes in wider, non-interacting binary systems, through the astrometric motion of their (visible) companion star.

I described the background, and the first of these discoveries, Gaia BH1 (Chakrabarti et al., 2023; El-Badry et al., 2023b), in essay 101. Gaia BH2 was discovered in a similar manner by El-Badry et al. (2023a). A third, Gaia BH3, was found by Panuzzo et al. (2024), with some illustrative animations here.

Other Gaia *candidates* include β Cyg (Albireo) (Bastian & Anton, 2018; Drimmel et al., 2021; Jack et al., 2022), and the Gaia DR3 objects G5870 (Tanikawa et al., 2023), and G3425 (Wang et al., 2024).

System	G (mag)	$M_{\rm bh}$	M_2	$P_{\rm orb}$ (d)	e	d (pc)
Gaia BH1	13.8	9.61	0.93	185	0.45	480
Gaia BH2	12.3	8.94	1.07	1280	0.52	1160
Gaia BH3	11.2	32.70	0.76	4250	0.73	590

Properties of these (bright) Gaia discoveries are summarised above. The published orbital solutions employ ground-based spectroscopy and radial velocities (of the visible component) to validate and refine the Gaia astrometric solution. For example, Gaia DR3 astrometry of Gaia BH1 defines a photocentric ellipse with a semi-major axis of only $a_0 = 3.00 \pm 0.22$ mas (El-Badry et al., 2023b). Their combined orbit solution used radial velocities from Magellan–E, Gemini–GMOS, VLT–X-Shooter, Keck–HIRES, ESO–FEROS, and Keck–ESI.

All three immediately entered the record books as the nearest known black holes, a distinction previously held by Cyg X1 (between 1975–86), and V616 Mon (from 1986 until the discovery of Gaia BH1 in 2023). And their proximity suggests that such wide black-hole binaries, while harder to detect than compact systems with ongoing accretion, must be significantly more common.

Also noteworthy are their large orbital periods, longer than any other black hole binaries. Follow-up searches have failed to detect radio or X-ray emission (El-Badry et al., 2023b, §7; El-Badry et al., 2023a, §3; Cappelluti et al., 2024; Gilfanov et al., 2024; Sjouwerman & Blanchard, 2024; Rodriguez et al., 2024), suggesting that the accretion rate at the event horizon is much lower than the Bondi–Hoyle–Lyttleton rate (El-Badry et al., 2023b, §3.12.2).

The third object, Gaia BH3, has attracted interest because of its high mass, $33 M_\odot$, more than any other Galactic stellar-origin black hole. This ties in with the fact that gravitational waves from black-hole mergers have pointed to a population of extragalactic black holes in short-period binaries with masses $30 - 85 M_\odot$ (Abbott et al., 2020; Abbott et al., 2021). These are more massive than predicted by most stellar evolution models, in which stars with an initial mass $M > 30 M_\odot$ lose most of their mass due to strong winds, resulting in observed black hole masses below $\sim 20 M_\odot$ (Vink, 2008; Belczynski et al., 2007; Sukhbold et al., 2016).

The suggestion that these more massive objects are the remnants of massive metal-poor stars (e.g. Belczynski et al., 2010) appears to be provisionally supported by the low metallicity of Gaia BH3's companion star, $[{\rm Fe/H}] = -2.56 \pm 0.11$.

As shown by Panuzzo et al. (2024), its Galactic orbit is consistent with the halo structure of both the Sequoia and ED-2 streams (essay 71), while its metallicity is more consistent with ED-2 ($[{\rm Fe/H}] \sim -2.6$) than with Sequoia ($[{\rm Fe/H}] \sim -1.7$). The association with ED-2, which likely originated from a disrupted globular cluster, perhaps M92, has been confirmed by Balbinot et al. (2024).

The formation of these systems is a challenge for standard evolutionary models for isolated binaries (El-Badry et al., 2023b, §8.4; El-Badry et al., 2023b, §5). For example, starting with a $25 M_\odot$ primary and a $1 M_\odot$ secondary, mass transfer through Roche-lobe overflow of the primary, and starting at separations 10 au or less, would lead to an episode of common envelope evolution (which I have described further in essay 204), during which the orbital separation would be reduced by a factor 100 or more, leading to a present separation a factor of at least 50 smaller than observed.

Other formation channels were noted in the discovery papers. The systems may have originated as very massive primaries that never became a red supergiant, so avoiding mass transfer altogether. They may have formed dynamically through an exchange interaction in a dense cluster. Or they may have originated as a triple system, with the observed 'secondary' being the outer component of an inner close binary, composed of two massive stars (e.g. Hayashi et al., 2023). High-precision VLT–ESPRESSO observations of Gaia BH1 appear to exclude this latter possibility (Nagarajan et al., 2024).

Later models find support for two of these alternative formation channels. Iorio et al. (2024) found that systems such as Gaia BH3 can indeed form from low-metallicity ($Z < 0.01$) binaries initially composed of a massive star ($40 - 60 M_\odot$) and a low-mass companion ($< 1 M_\odot$) in a wide ($P > 10^3$ d) and eccentric ($e > 0.6$) orbit. Such systems never undergo Roche-lobe overflow, and the final orbital properties are largely determined at the core collapse of the primary. They suggested that some 4000 star–black hole systems in the Galactic halo have been formed in this way, of which ~100 are compatible with the properties of Gaia BH3, with only one at the distance of Gaia BH3.

Meanwhile, Marín Pina et al. (2024) used N-body simulations to show that such systems can be assembled dynamically in globular clusters. They estimate that the Galaxy halo contains of order 10^5 such systems, some of which may be detected in Gaia DR4 (see also Liu et al., 2022; Generozov & Perets, 2024; Li et al., 2024). Other explanations have been given by Gilkis & Mazeh (2024).

Future Gaia releases, DR4 and DR5, will likely identify dozens of similar systems (Yamaguchi et al., 2018; Shikauchi et al., 2020; 2022; Janssens et al., 2022; Chawla et al., 2022; El-Badry et al., 2023b, §10).

These will provide valuable tests of black hole formation, cluster dynamics, and their contribution to observable gravitational wave sources (Shikauchi et al., 2023).

They may also provide a direct test of whether black hole growth follows cosmological expansion (Andrae & El-Badry, 2023), motivated by the suggestion that stellar remnant black holes could be the astrophysical origin of dark energy, and the onset of accelerating expansion at $z \sim 0.7$ (Farrah et al., 2023a; Farrah et al., 2023b).