175. Black holes in open clusters

It has recently become clear that the existence of stellar mass black holes should have observable consequences on the overall dynamics of open clusters and stellar streams, placing useful constraints on their formation. I will look at some early results for the Hyades open cluster in this essay, and at their effect on the morphology and kinematics of halo streams in the following.

Let me start with some context. The very existence of stellar mass black holes can be demonstrated in various ways. A black hole in a close binary system can be inferred from X-ray emission due to accreted material; through the astrometric motion of its visible companion; as ellipsoidal light variations due to tidal distortion of its companion; and, at the end of their orbital life, as a gravitational wave burst accompanying the system's final inspiral and merger. Isolated black holes may be revealed through the effects of gravitational microlensing.

I have given an introduction to Gaia's contributions to gravitational wave searches in essays 131 and 136, and to the class of ellipsoidal variables in essay 133. In essay 101, I outlined some of the searches for black holes in X-ray binaries (a catalogue is maintained by Corral-Santana et al., 2016), from astrometric binary motions, and for isolated microlensing searches.

From Gaia DR3 astrometry, three non-interacting (X-ray quiescent) binary black hole candidates have been reported: Gaia BH1 with $M_{\rm BH} = 9.6 M_\odot$ at 480 pc (El-Badry et al., 2023b), and Gaia BH2 with $M_{\rm BH} = 8.9 M_\odot$ at 1.2 kpc (El-Badry et al., 2023a), making them the nearest known black hole candidates. The third, Gaia DR3 5870569352746779008, is a $> 5.6 M_\odot$ black hole in a 1350 d binary, discovered from a study of more than 60 000 DR3 binary solutions with both astrometric and spectroscopic data (Tanikawa et al., 2023).

Beyond Gaia, only one other non-interacting massive black hole candidate appears to be rather secure: the single-lined spectroscopic binary VFTS 243 in the Large Magellanic Cloud (Shenar et al., 2022). It comprises an O star of $25 M_\odot$ and an unseen companion of $> 9 M_\odot$, in a binary system with orbital period 10.4 d.

The most recent Gaia DR3-based photometric microlensing searches for isolated black holes have so far generated only a small number of unconfirmed *candidates* (Kruszyńska et al., 2024). This leaves OGLE–2011–BLG–0462 (aka MOA–2011–BLG–191) as the only microlensing black hole. Models indicate a distance of 1.5 kpc, and a lens (black hole) mass of $6 - 8 M_\odot$ (Sahu et al., 2022; Mróz et al., 2022; Lam & Lu, 2023).

With the X-ray black hole candidates lying at typical distances of 2 kpc or more, this leaves the non-interacting binary systems Gaia BH1 and Gaia BH2 as the nearest known black holes.

And this class of object is important for understanding the evolutionary pathways leading to the merging black holes observed by LIGO/VIRGO, and in particular the role of natal 'kicks' during supernova core collapse (e.g. Mandel & Farmer, 2022; Mandel & Broekgaarden, 2022). In interacting (X-ray) binaries, tidal forces circularise the binary orbit, suppressing information on these kicks previously encoded in the system's eccentricity. In contrast, weakly interacting (X-ray quiescent) binaries preserve the black-hole kick signatures in their orbits.

Stars expand dramatically beyond the main sequence, and early merging is only avoided if the initial orbit is rather wide. Models explaining the existence of these double compact binaries, which can then merge within a Hubble time, generally invoke a 'common-envelope' phase (e.g. Portegies Zwart et al., 1997; Tauris et al., 2017), allowing the system to shrink to a compact final configuration. The process is incompletely understood, and the formation of Gaia BH1 consequently uncertain (El-Badry et al., 2023b; Shikauchi et al., 2023).

Other models have considered a very different formation mechanism, viz. through dynamical interactions in a young star cluster (e.g. Portegies Zwart & McMillan, 2000; Shikauchi et al., 2020; Rastello et al., 2023). In these scenarios, the Gaia black hole binaries may be the inner binary of a triple star system in which Lidov–Kozai resonance oscillations also operate (Hayashi et al., 2023; Generozov & Perets, 2023; Tanikawa et al., 2024).

The discovery of accreting black hole candidates in globular clusters, both extragalactic (Maccarone et al., 2007), and within the Milky Way (Strader et al., 2012; Chomiuk et al., 2013; Miller-Jones et al., 2015) has motivated specific studies of the formation of binary black holes in the centres of globular clusters (Portegies Zwart & McMillan, 2000; Antonini & Gieles, 2020), and indeed in open clusters (Di Carlo et al., 2019; Rastello et al., 2019; Kumamoto et al., 2020; Banerjee, 2021; Torniamenti et al., 2022). These discoveries already demonstrated that stellar interactions would not eject *all* of the black holes that might form in globular clusters (Kulkarni et al., 1993; Sigurdsson & Hernquist, 1993).

Other evidence for stellar mass black holes in globular clusters has been gathered from their large core radii, the lack of mass segregation, their mass-to-light ratio, and their tidal tails (for references, see Torniamenti et al., 2023). For example, and in a topic I will pick up in my next essay, N-body simulations of the halo globular cluster Palomar 5 can explain both its large extent and its extended tidal tails in models with 20% of its total mass in the form of stellar-mass black holes (Gieles et al., 2021).

According to Torniamenti et al. (2023), these kinds of dynamical searches for black hole populations in stellar clusters have focused on old ($\gtrsim 10\,$Gyr) and relatively massive ($\gtrsim 10^4 M_\odot$) globular clusters in the Milky Way halo, with no such searches in young open clusters in the disk because of the limited phase-space (position and velocity) information hitherto available for them.

The situation has changed with Gaia, which has brought the discovery of hundreds of new open clusters, and a wealth of membership details along with accurate morphological and kinematic data now available for many (see, e.g. Cantat-Gaudin, 2022; and essays 74 and 144). This offers the prospects of quantifying their radial distributions out to their outermost regions (Tarricq et al., 2022), their extended halos (Meingast et al., 2021), and tracing the tidal tails of clusters including the Hyades (essay 20), Blanco 1, and Praesepe.

The N-body code `PETAR`, combined with the `galpy` code for the Galaxy potential (Bovy, 2015), was used by Wang & Jerabkova (2021) to simulate the evolution of star clusters along with their tidal streams in various Galactic potentials. The most massive OB stars, and black holes, have a major effect, with clusters having the same initial conditions, but a different initial content of OB stars, following very different evolutionary paths.

As a consequence, the total initial mass and radius of an open star cluster cannot be unambiguously determined unless the initial content of OB stars is known. They showed that the stellar counts in the associated tidal tails, that can in principle be identified from the Gaia data, would help to resolve these uncertainties.

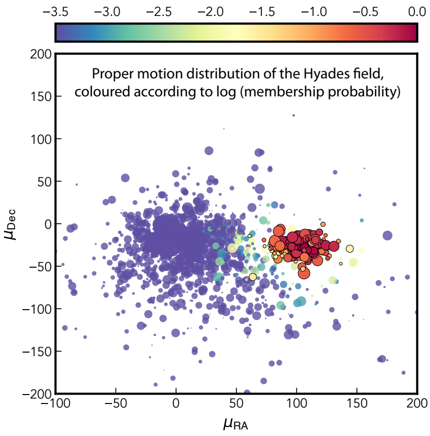
The first searches for such dynamical evidence for black holes in open clusters using this approach, and indeed following the same methods used in the Palomar 5 globular cluster study by Gieles et al. (2021), has been reported for the Hyades cluster, and using the Gaia DR3 data, by Torniamenti et al. (2023).

They generated a large suite of N-body models, as developed by Wang & Jerabkova (2021), and compared them with the radial profile of Hyades members, using masses derived from the Gaia DR3 data by Evans & Oh (2022). Their objective was to ascertain whether a residual black hole population is required to explain the observed structure. Models of binary black hole mergers, in which a significant fraction of stellar-mass black holes must receive negligible natal kicks to explain the gravitational wave detections, imply that black holes could and should be retained even in open clusters with low escape velocities of $\lesssim 1\,\mathrm{km\,s^{-1}}$.

Torniamenti et al. (2023) found that their Gaia DR3 observations are best reproduced by models with 2–3 black holes still in the Hyades cluster today. Models that never possessed black holes would have a half-mass radius significantly smaller than observed, while models in which the last remaining black holes were ejected recently, say 150 Myr ago, can still reproduce the observed radial density profile. In these model, the ejected (binary) black holes are at a typical distance of 60 pc from the cluster centre, and some 80 pc from the Sun.

In half of their models, the black holes were in binary systems with stellar companions. But their period distribution peaks at $\sim 10^3$ yr, and they are therefore unlikely to be found from orbital velocity variations. They identified 56 binary candidates on the basis of their large astrometric and spectroscopic errors, none of which were consistent with a massive compact companion.

Their models with 2–3 black holes had an elevated central velocity dispersion, which cannot yet be verified from the current observations. Nonetheless, one conclusion of their study is that the nearest stellar-mass black holes to the Sun are in, or near, the Hyades cluster!



Torniamenti et al. (2023)