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LETTER TO THE EDITOR

The $33 M_{\odot}$ black hole *Gaia* BH3 is part of the disrupted ED-2 star cluster

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ABSTRACT

Context. The *Gaia* Collaboration has recently reported the detection of a $33 M_{\odot}$ black hole in a wide binary system located in the solar neighbourhood.

Aims. Here we explore the relationship between this black hole, known as *Gaia* BH3, and the nearby ED-2 halo stellar stream.

Methods. We studied the orbital characteristics of the *Gaia* BH3 binary and present measurements of the chemical abundances of ED-2 member stars derived from high-resolution spectra obtained with the VLT.

Results. We find that the Galactic orbit of the *Gaia* BH3 system and its metallicity are entirely consistent with being part of the ED-2 stream. The characteristics of the stream, particularly its negligible spread in metallicity and in other chemical elements, as well as its single stellar population, suggest that it originated from a disrupted star cluster of low mass. Its age is comparable to that of the globular cluster M92 that has been estimated to be as old as the Universe.

Conclusions. This is the first black hole unambiguously associated with a disrupted star cluster. We infer the plausible mass range for the cluster to be relatively narrow, between $2 \times 10^3 M_{\odot}$ and $5.2 \times 10^4 M_{\odot}$. This implies that the black hole could have formed directly from the collapse of a massive very metal-poor star, but that the alternative scenario of binary interactions inside the cluster environment also deserves to be explored.

Key words. stars: abundances – stars: black holes – stars: Population II – globular clusters: general – Galaxy: halo – Galaxy: kinematics and dynamics

1. Introduction

The discovery of a $33 M_{\odot}$ black hole (BH) was recently reported in the *Gaia* DR4 pre-release data ([Gaia Collaboration 2024](#)). This BH is in a wide binary system with a period of 11.6 years. Its visible companion (*Gaia* DR3 source_id 4318465066420528000) is a known high proper motion star that is part of the Galactic halo. The low metallicity $[\text{Fe}/\text{H}] = -2.56 \pm 0.12$ reported by [Gaia Collaboration \(2024\)](#) confirms the association with this Galactic component.

This discovery is especially exciting in light of the enormous advances made in the field of gravitational waves in recent years. Several tens of detections of gravitational waves due to merging binary BHs have been reported by the LIGO/VIRGO/KAGRA collaboration ([Abbott et al. 2023a](#)). The modelling of these events has revealed that the binary BH mass distribution follows a power law, with peaks at chirp masses of $\sim 8 M_{\odot}$ and $\sim 28 M_{\odot}$ ([Abbott et al. 2023b](#)). The origin of the heavier BHs is not well understood. Because very massive stars of solar metallicity lose much of their mass via stellar winds, it has been argued that many of these BHs could reside in metal-poor environments such as dwarf galaxies. An alternative pathway could be dynamical interactions in dense star clusters, which may lead to hierarchical growth of BH via BH binary mergers (see e.g. [Antonini & Gieles 2020](#); [Fragione & Rasio 2023](#)). In this context, it is important to shed more light on the origin of *Gaia* BH3.

Since *Gaia* BH3 has a very retrograde and relatively loosely bound orbit, [Gaia Collaboration \(2024\)](#) have argued for a possible association with the Sequoia accretion event ([Myeong et al. 2019](#)) identified using *Gaia* DR2 data. The better astrometry available in the subsequent *Gaia* (E)DR3, has revealed however that this region of integrals of motion (IoM) space (e.g. energy and angular momenta) contains several additional substructures in addition to Sequoia (e.g. [Ruiz-Lara et al. 2022](#); [Dodd et al. 2023](#)). Some of these substructures appear to have distinct chemistry ([Matsuno et al. 2019](#); [Naidu et al. 2020](#)).

Among the smaller of such retrograde structures first identified by [Dodd et al. \(2023\)](#) we highlight ED-2. This substructure has been shown to form a dynamically cold stellar stream crossing the solar neighbourhood ([Balbinot et al. 2023, B23](#)). Because of the dynamical properties of ED-2 (a cold but relatively wide stream) it was suggested that it could have originated from an ultra-faint dwarf galaxy. On the other hand, the tight distribution of its member stars in colour-magnitude space and the relatively narrow (rms ~ 0.2 dex) metallicity distribution measured from LAMOST DR3 low-resolution spectra ([Li et al. 2018](#)) for seven stars, favoured a star cluster origin. Interestingly, the mean metallicity of ED-2 stars is $[\text{Fe}/\text{H}] = -2.60^{+0.20}_{-0.21}$, suspiciously close to that of the companion of *Gaia* BH3.

In this Letter we demonstrate that *Gaia* BH3 is indeed associated with the cold stellar stream ED-2 and that ED-2 stems from a low-mass disrupted star cluster. Section 2 focuses on

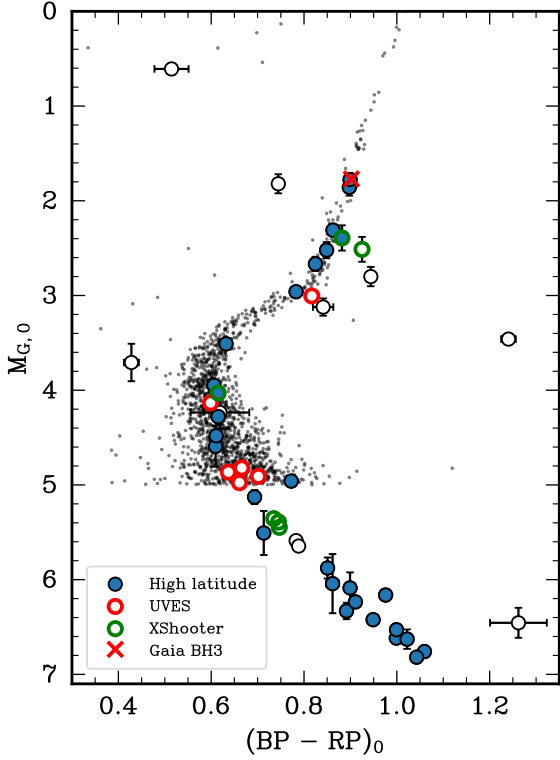


Fig. 1. *Gaia* DR3 extinction-corrected CMD showing the location of the *Gaia* BH3 companion as a red cross, and the ED-2 members (B23) as blue and empty circles. The former are high-latitude ($|b| > 20^\circ$), low-extinction ($E(B - V) \leq 0.01$) ED-2 members. The sequence followed by the ED-2 stars is extremely tight, indicative of their small metallicity dispersion. Their distribution is in very good agreement with the CMD of stars in the globular cluster M92 (truncated at $M_{G,0} = 5$), shown in the background as black dots. This implies that they are of similar age, given their comparable metallicities. The object with $M_{G,0} \sim 0.6$ is an RR Lyrae type-c star (Clementini et al. 2023).

the dynamical association of *Gaia* BH3 with ED-2, and Sect. 3 presents chemical abundances from follow-up X-Shooter and UVES spectra of ED-2 members¹. In Sect. 4 we discuss the implications of our findings, and in Sect. 5 we present our conclusions.

2. Kinematics and stellar population

Figure 1 shows the extinction-corrected colour-magnitude diagram (CMD) for all ED-2 members (see B23 for details). The cross indicates the location of the *Gaia* BH3 companion star (which due to the high RUWE value reported in *Gaia* (E)DR3, was left out of the analysis by Dodd et al. 2023). The error bars in this figure account for the effects of distance and extinction uncertainty. All ED-2 known member stars are within 2.5 kpc of the Sun, and their relative distance errors are smaller than 20%. We compute the extinction at $d \pm 3\epsilon_d$ (where ϵ_d is the distance error) to conservatively estimate the error introduced in the 3D extinction maps of Lallement et al. (2022). These uncertainties are summed in quadrature with the photometric uncertainty.

¹ These data had been requested in proposals 0111.D-0263(A) (PI:Dodd) and 112.25ZW.001 (PI:Balbinot), and hence submitted before the analyses that led to the discovery of *Gaia* BH3. The co-Is of both proposals are co-authors of this paper who are not members of the *Gaia* Collaboration.

For comparison, we also plot members of the globular cluster M92 in the background. These were selected using the method of Vasiliev & Baumgardt (2021) and are at least $4'$ away from M92's centre, to avoid crowding. The CMD of M92 has been extinction corrected following the recipe described above.

This comparison shows that ED-2 stars closely match the CMD of M92, which is known to be one of the oldest and most metal-poor ($[Fe/H] \sim -2.3$) globular clusters (GCs) in the Galaxy (Ying et al. 2023), with an age of 13.80 ± 0.75 Gyr. Since the main-sequence turn-off (MSTO) seems to be slightly fainter, ED-2 could potentially be even older; however, this is supported by only a single MSTO star in ED-2. In any case, we can conclude from this comparison that ED-2 formed more than 13 Gyr ago.

Figure 2 shows the distribution of ED-2 stars in IoM space: z -angular momentum versus energy (top panel), and versus the perpendicular component of the angular momentum (bottom panel). The location of *Gaia* BH3 is indicated with a cross and falls right on top of the ED-2 stream members. We note that the values of the IoM were computed in the Milky Way potential of Dodd et al. (2023), which is slightly different from that used in *Gaia* Collaboration (2024). The Mahalanobis distance² between the centre of ED-2 and *Gaia* BH3 is 0.942, while that between Sequoia and *Gaia* BH3 is 2.718. In other words, only 17% of the members of ED-2 are closer to its centre than *Gaia* BH3, while it is in the outskirts of Sequoia as 94% of its stars have a smaller distance. This makes it much more likely that *Gaia* BH3 is associated with ED-2 than with Sequoia.

This is further illustrated by the trajectories followed by the stars in ED-2 and *Gaia* BH3 shown in Fig. 3, where there is no noticeable distinction between the different objects. It is interesting that BH3 is not at the centre of the distribution of stars. Whether this is real or due to incompleteness in the sample (i.e. the distance limit and the magnitude limit of the RVS dataset) should be explored more thoroughly in further studies.

Given the size of the ED-2 structure in IoM space, which is comparable to that of other globular clusters, such as NCGC3201 and NGC6101 (also shown in Fig. 2), we tentatively conclude that ED-2 stems from a GC-like progenitor. The good fit obtained from a single stellar population further supports this conclusion.

3. Chemical abundances

We obtained spectra for three stars as part of the follow-up of the ED-2 stream in period 111 (April–September 2023; proposal submitted in September 2022) with the optical spectrograph, UVES (Dekker et al. 2000) mounted at the Very Large Telescope (VLT) of the European Southern Observatory (ESO). We also used ESO archival data for another ED-2 member, source_ID 4479226310758314496. Additionally, we observed six ED-2 core members with X-Shooter (Vernet et al. 2011) at the VLT in period 112 (October 2023–March 2024; proposal submitted in March 2023). In all cases, we used the phase-3 data products provided by ESO for further analysis. In the Appendix we provide details of the observational set-ups, and we also describe the procedure used to derive the stellar parameters and chemical abundances of the UVES stars and the $[Fe/H]$ for the

² The Mahalanobis distance between BH3 and ED-2 (Sequoia) is defined as $D_{BH3}^2 = (\mu_i - \mu_{BH3})^T \Sigma_i^{-1} (\mu_i - \mu_{BH3})$, where μ_{BH3} denotes the location of BH3 in IoM space and μ_i and Σ_i are the mean and covariance matrix of the ED-2 (Sequoia) stars.

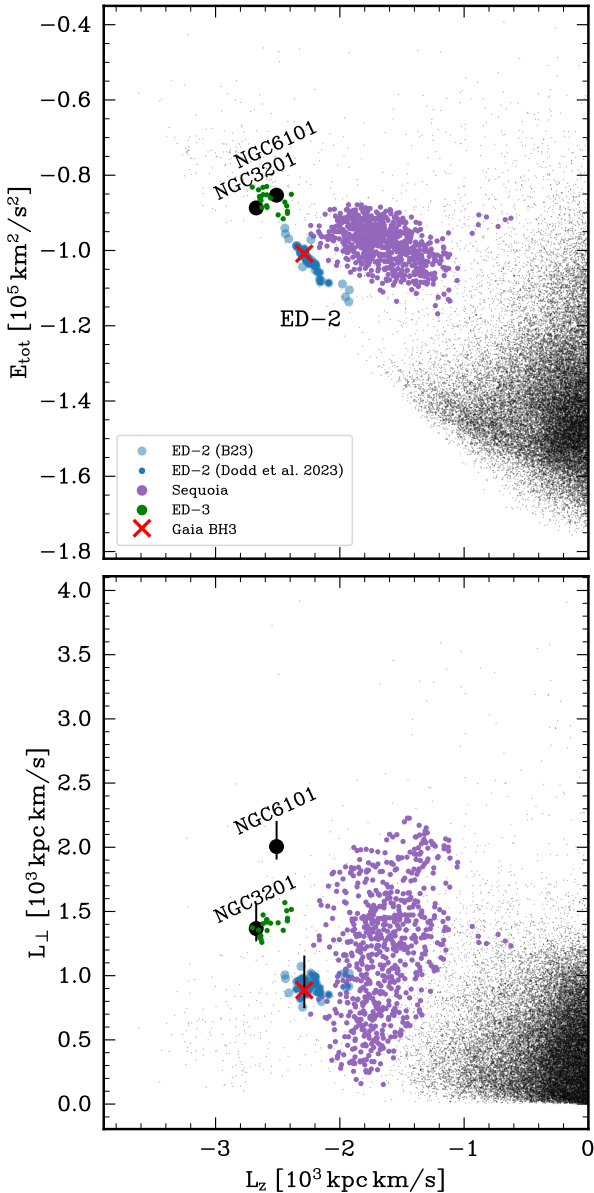


Fig. 2. L_z vs. E_{tot} (top panel) and vs. L_{\perp} (bottom panel) showing ED-2 as blue and lighter blue circles, corresponding respectively to original members from Dodd et al. (2023) and to the extended sample (see B23 for details). *Gaia* BH3 is shown as a red cross. Members of ED-3 and Sequoia (as classified by Dodd et al. 2023) are also shown. The dark points in the background are from the *Gaia* DR3 6D sample within 3 kpc and $\text{RUWE} < 1.4$. We also show two retrograde GCs. The vertical error bars show the variation in L_{\perp} for ED-2 and the two GCs along their orbits.

X-Shooter targets. We list the results in Table A.1 and Table A.2 for the stars observed with UVES and X-shooter respectively.

Figure 4 shows the metallicity distribution derived for the ED-2 stars in our programs. The top panel corresponds to the UVES targets whose metallicity is measured from the Fe II lines, which are more reliable due to their low sensitivity to the adopted stellar parameters and non-local thermodynamic equilibrium (NLTE) effects. The middle panels are for the X-Shooter stars, while the bottom panel shows the distribution derived by B23 compared to that of Sequoia as defined by Dodd et al. (2023), both using LAMOST spectra. The black arrow and error bar show the *Gaia* BH3 visible companion’s metallicity and its

uncertainty. This figure confirms, now on the basis of the metallicity, that the black hole is a member of ED-2, and has a negligible probability that it is a part of Sequoia.

We measured the mean metallicity and metallicity dispersion ($\sigma_{[\text{Fe}/\text{H}],\text{int}}$) of ED-2 in the UVES and X-Shooter samples assuming a simple normal distribution with dispersion $\sigma^2 = \sigma_{[\text{Fe}/\text{H}],\text{int}}^2 + \sigma_{[\text{Fe}/\text{H}],j}^2$ (i.e. the sum in quadrature of an intrinsic dispersion and the metallicity uncertainty in each j th data point). We used this distribution to maximise the likelihood of our model using EMCEE (Foreman-Mackey et al. 2013). For the UVES sample, we find a best-fit metallicity of $[\text{Fe}/\text{H}]_{\text{II}} = -2.46 \pm 0.02$ and a metallicity dispersion $\sigma_{[\text{Fe}/\text{H}]} < 0.04$. Similarly, for the X-Shooter sample, we find a best-fit metallicity of $[\text{Fe}/\text{H}] = -2.51 \pm 0.07$ and a metallicity dispersion $\sigma_{[\text{Fe}/\text{H}]} < 0.07^3$. The uncertainties in metallicity were computed from the standard deviation of the posterior distribution, while the upper limits in $\sigma_{[\text{Fe}/\text{H}]}$ are the 67% quantile of the posterior. We thus find that the intrinsic metallicity dispersion of ED-2 is consistent with zero. This favours a star cluster origin as opposed to a dwarf galaxy, as even ultra-faint dwarfs have a scatter of at least 0.3 dex (Simon 2019).

Figure 5 shows the abundances of Mg, Na, and Al with respect to Fe for the stars observed with UVES (blue triangles). The scatter in all elements is very small, again indicating that the ED-2 originated in a star cluster. The abundances measured for other ED-2 stars by Ceccarelli et al. (2024, green diamonds) also show very comparable values. The measurements for the companion star of *Gaia* BH3 as provided by Gaia Collaboration (2024, in orange) and by our own analysis (in red) are fully consistent with those of the ED-2 stars. Its measured $[\text{Eu}/\text{Fe}] = 0.52$ is also in excellent agreement with that of another star in ED-2 for which we could measure $[\text{Eu}/\text{Fe}] = 0.61$, a value that supports similar amounts of r -process enhancement across the system. The ED-2 mean abundance of $[\text{Ba}/\text{Fe}] \sim -0.22$ (and its small dispersion of 0.1 dex) is consistent with that of other halo stars, but different from that seen in ultra-faint dwarf galaxies, which typically depict much higher or much lower values (Ji et al. 2019). In Fig. 5 we plotted for comparison the abundances of a set of GCs from Carretta et al. (2009, all of which are more metal-rich), which reveal a scatter in $[\text{Mg}/\text{Fe}]$ similar to that of ED-2 members, but larger in Na and Al. At the metallicity of ED-2, MW GCs present a median $[\text{Al}/\text{Mg}]$ spread of ~ 0.5 dex (Pancino et al. 2017). Our estimate for the intrinsic spread using the four UVES ED-2 members (obtained following the procedure described above) is $0.11^{+0.08}_{-0.05}$ where the uncertainties correspond to the 25 and 75 percentiles, and therefore is significant smaller.

The low $[\text{Al}/\text{Fe}]$ and high $[\text{Mg}/\text{Mn}]$ of the ED-2 stars and of the companion star of *Gaia* BH3 (see Table A.1) places ED-2 members in a region of abundance-space that is referred to as ‘chemically unevolved’ (Hawkins et al. 2015; Fernandes et al. 2023). This could hint at an accretion origin of ED-2 also given its highly retrograde orbit. However, care must be taken when interpreting this chemical space since its validity as an indicator of a possible accretion origin has not been firmly established for star clusters.

³ Although the star with source_ID 3757312745743087232 is more metal-rich than the remainder of the sample (see Table A.2), it has very large uncertainties, and its inclusion has no effect in the derived mean and spread in metallicity.

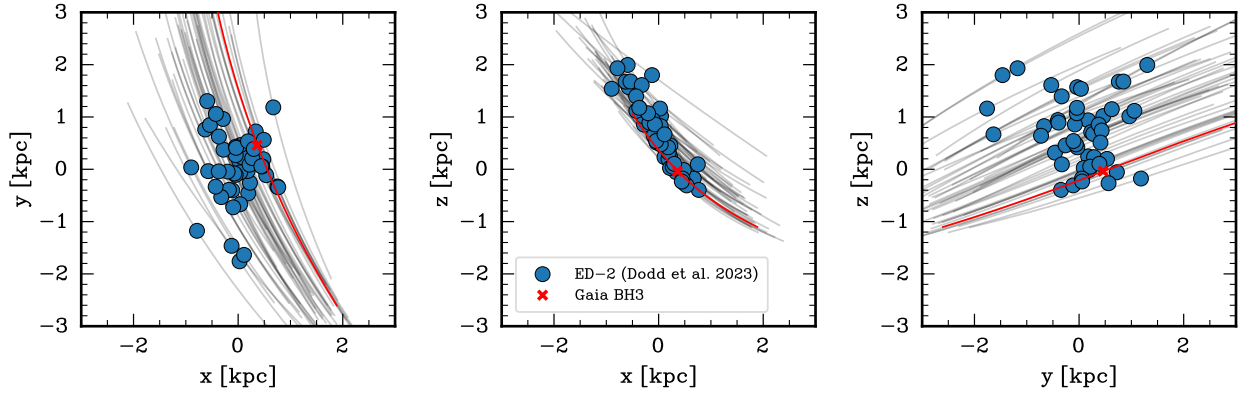


Fig. 3. Cartesian heliocentric projection of the location of ED-2 members and their orbits integrated in the Milky Way potential used in Dodd et al. (2023) for 20 Myr. The red cross and line show the position and orbit of *Gaia* BH3, and is indistinguishable from that of the ED-2 stars.

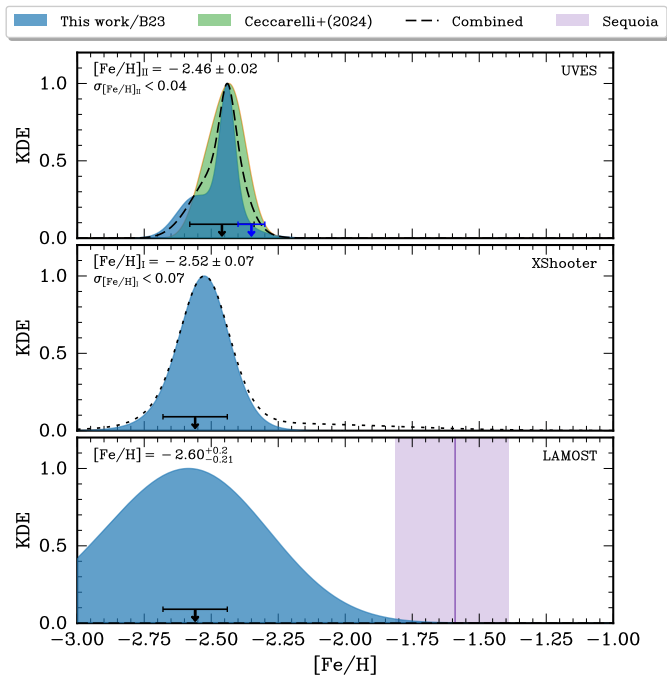


Fig. 4. Metallicity distribution for ED-2 based on UVES, X-Shooter, and LAMOST spectra in the top, middle, and bottom panels, respectively. The arrow and error bar show the *Gaia* BH3 companion’s metallicity and uncertainty, as inferred by Gaia Collaboration (2024), in the top panel, using Fe II lines and by our own analysis in blue (see also Table A.1). In the top left of each panel the best-fit metallicity and the upper bound on the metallicity dispersion are given. In the middle panel, the dashed distribution includes a star with large [Fe/H] uncertainties. In the bottom panel the 25%–75% quantiles for members of Sequoia (following the classification of Dodd et al. 2023) are shown as a shaded band using metallicity estimates from LAMOST.

4. Discussion

Having established that *Gaia* BH3 formed in a star cluster, we now explore possible formation channels. We also attempt to infer some properties of the ED-2 parent cluster. We note that these findings naturally explain the ‘normal’ chemical composition of its accompanying star, in the sense that the binary could easily have formed in the cluster after the BH was born.

The most straightforward formation scenario for BHs is through the collapse of a very massive star. The mass of such

a BH is dictated by the star’s mass at the end of its evolution. Due to the details of the mass-loss process, this can differ significantly from its initial value. Using the single-star initial-final mass relations (IFMRs) from Fryer et al. (2012) implemented in *ssptools*⁴ (Balbinot & Gieles 2018; Dickson et al. 2023) and a Kroupa initial mass function, we can infer how many stellar BHs of a given mass are likely to form as a function of the cluster mass. We find that the minimum mass for a star cluster to host at least one stellar BH of the size of *Gaia* BH3 or greater is $M_{\text{cl,min}} \sim 2 \times 10^3 M_{\odot}$. In this case, *Gaia* BH3 would be a first generation BH.

Alternative pathways to produce very massive BHs have been proposed that require binary evolution and dynamical hardening of these binary systems. These processes take place in dense stellar systems such as GCs (see e.g. Portegies Zwart & McMillan 2000), and see also the recent work by Rastello et al. (2023), Tanikawa et al. (2024), and Di Carlo et al. (2024) on young star clusters. Due to their stochastic nature, such processes can produce BHs with a wide range of masses (see e.g. Antonini & Gieles 2020). In this case, *Gaia* BH3 could have formed via the mergers of subsequent generations of BHs.

The scatter in the Na and Al abundances seen in GCs is indicative of multiple stellar populations (MSP) and has a dependence on both mass and metallicity (see e.g. Gratton et al. 2019). Fnx I, a GC in the Fornax dwarf spheroidal, has [Fe/H] ~ -2.5 , and shows multiple populations, as well as a significant scatter in [Na/Fe] (Letarte et al. 2006), and its initial mass has been estimated to be $4.2 \pm 1.0 \times 10^4 M_{\odot}$ by de Boer & Fraser (2016)⁵. Therefore, the very small scatter in light element abundances for ED-2 suggests its parent cluster was lower in mass than Fnx I. We thus adopt for ED-2 an upper mass limit of $5.2 \times 10^4 M_{\odot}$.

A relationship between the scatter in [Al/Fe], the mean [Fe/H] of a cluster and its mass has been put forward by Pancino et al. (2017) for Galactic clusters: $\sigma[\text{Al}/\text{Mg}] = 0.19(\pm 0.06) \log M_{\text{cl}} - 0.20(\pm 0.05)[\text{Fe}/\text{H}] - 0.94(\pm 0.33)$. From the distribution of $\sigma[\text{Al}/\text{Mg}]$ values given by the MCMC chain of Sect. 3, and considering the uncertainties in the coefficients in a similar fashion, we can therefore infer a distribution of

⁴ <https://github.com/SMU-clusters/ssptools>

⁵ This value is in good agreement with that of Baumgardt et al. (2023), after correction for mass-loss due to stellar evolution (Lamers et al. 2010). Corrections for dynamical mass-loss have not been included in these estimates, but they are likely to be small because Fnx I is located in the outskirts of Fornax where the tidal field is considerably lower than that of the MW (Baumgardt & Makino 2003).

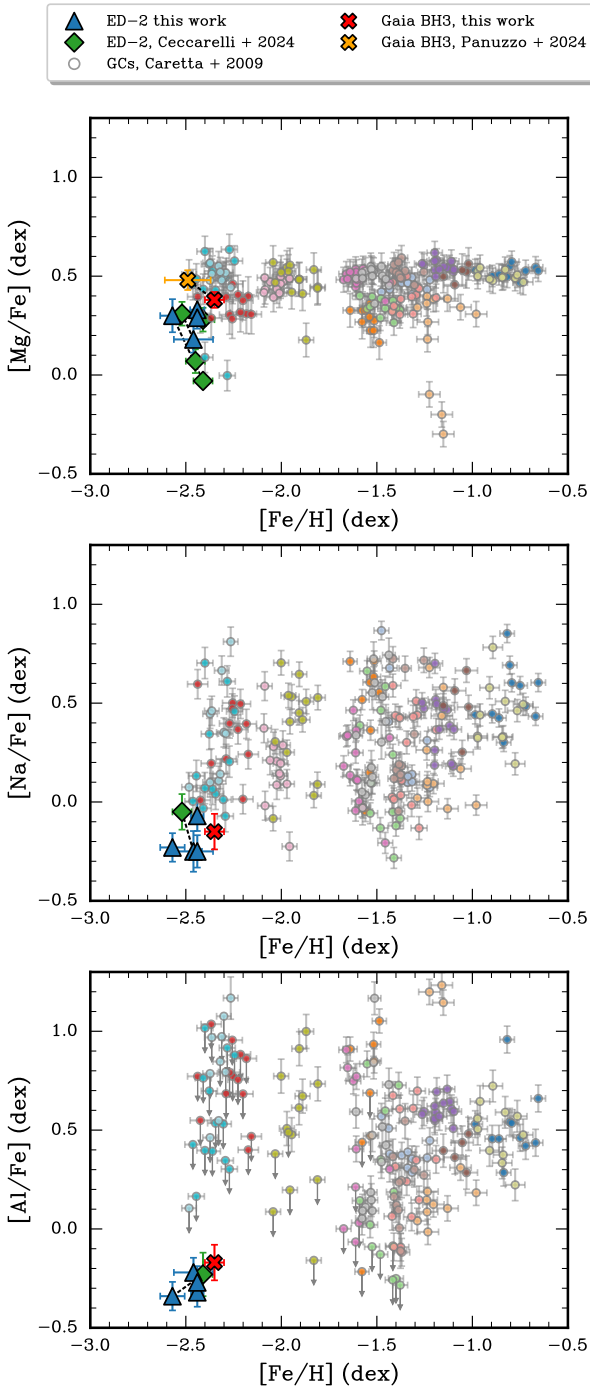


Fig. 5. Abundances of Mg/Fe, Na/Fe, and Al/Fe for the four ED-2 stars in our UVES sample (blue triangles), and for ED-2 stars from Ceccarelli et al. (2024, green diamonds). There is good agreement and small scatter. The companion of *Gaia* BH3 is chemically indistinguishable from the ED-2 stars. The red cross (×) corresponds to our own abundances and orange to the measurements from Gaia Collaboration (2024) (see text and Table A.1). For comparison, we have also plotted the upper limits to the abundances for several GCs from Carretta et al. (2009).

possible cluster masses for ED-2. We find a median value of $\log M_{\text{cl}}/M_{\odot} = 3.02$, with the 25% and 75% quantiles of $\log M_{\text{cl}}/M_{\odot}$ being 1.75 and 4.59, respectively. We note, however, that this estimate is based on an extrapolation of a relation determined for GCs whose metallicities are all higher than

ED-2's, and that this relation uses present-day masses. These masses will differ from their initial values due to mass loss associated with stellar evolution (Lamers et al. 2010) and to dynamical mass loss, and on average in total this amounts to a factor of 4 (Baumgardt & Sollima 2017). Despite the caveats, it is reassuring that the range of plausible masses inferred is consistent with that provided by the comparison to Fnx I.

Further support for ED-2 having been a low-mass star cluster comes from the fact that the *Gaia* BH3 system is a relatively wide binary, with a period of 11.6 yr. Such long period binaries do not survive in massive GCs because they are either quickly disrupted or become tighter because of interactions within such systems (Ivanova et al. 2005, although its low mass-ratio enhances the chances of survival). Unlike NGC6101 or NGC3201, the two GCs with similar orbits plotted in Fig. 2, ED-2 did not manage to survive as a star cluster until the present day. This could be due to its lower mass or to lower density, but the retention of *Gaia* BH3 by the ED-2 cluster could also have contributed to speeding up its disruption (Gieles et al. 2021).

5. Conclusions

In this Letter, we have shown that the $33 M_{\odot}$ black hole *Gaia* BH3 is associated with the ED-2 retrograde halo stellar stream. The BH's orbit around the Galaxy is indistinguishable from that of ED-2 members. Using high-resolution spectra of ED-2 stars, we have determined that ED-2's mean metallicity is entirely consistent with that of the companion of *Gaia* BH3, as are other chemical elemental abundances such as [Mg/Fe], [Eu/Fe], and [Ba/Fe]. Furthermore, we have shown that the metallicity spread in ED-2 is consistent with zero, indicating that it stems from a disrupted star cluster. This is entirely in line with its colour-magnitude diagram, which is very well fit by an extremely old single stellar population, similar to that of the GC M92, indicating that the progenitor of *Gaia* BH3 formed more than 13 Gyr ago. The (near) lack of scatter in Na and Al suggests that ED-2's parent system was a small cluster with mass lower than $5.2 \times 10^4 M_{\odot}$. This would leave a small window for *Gaia* BH3 to be the direct result of the collapse of a massive star, since we have found that such a heavy BH can only form in a system more massive than $2 \times 10^3 M_{\odot}$. To shed more light on its formation channels, sophisticated dynamical models of the ED-2 parent cluster, including stellar evolution and binary interactions, and using as boundary conditions those inferred in this paper (e.g. mass range, metallicity, and orbit) are needed. Furthermore, the mapping of the ED-2 stream beyond the solar neighbourhood would allow a reliable and independent determination of the initial cluster mass. Finally, detailed chemical abundances for more of its members would put a tighter constraint on the lack of a spread of light elements and constrain further the evolution of the system.

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Appendix A: Derivation of stellar parameters and chemical abundances of ED-2 stars

We obtained spectra for three stars as part of the follow-up of the ED-2 stream in period 111 (April–September 2023; proposal submitted in September 2022; programme 0111.D-0263(A), PI:Dodd) with the optical spectrograph, UVES mounted at the Very Large Telescope (VLT) of the European Southern Observatory. The observations were performed with UVES in dichroic mode adopting the standard settings Dic 1 Blue Arm CD2 390 (326–454 nm) and Dic 1 Red Arm CD3 580 (476–684 nm) and with the 0.7'' slit width, thus yielding a resolution of $R \sim 55\,000$, and $S/N \geq 15$ for the Blue Arm and $S/N \geq 30$ for the Red Arm on average. We also used ESO archival data from the programmes 0109.B-0522(A) and 167.D-0173(A), for another ED-2 member, `source_id` 4479226310758314496. Additionally, we observed seven ED-2 stars with X-Shooter at the VLT in period 112 (October 2023–March 2024; proposal submitted in March 2023; programme 112.25ZW.001; PI: Balbinot). In all cases, we used the phase-3 data products provided by ESO for further analysis.

For the UVES spectra we derived the chemical abundances of the stars using the 1D LTE spectral synthesis code MOOG (Snedden 1973) with the grid of MARCS model atmospheres (Gustafsson et al. 2008). Stellar parameters (T_{eff} and $\log g$) were determined from dereddened photometry and astrometry; T_{eff} was obtained from the $G - K_s$ colour using the relation from Mucciarelli et al. (2021), and $\log g$ was obtained from the K_s magnitude together with the bolometric correction of Casagrande & Vandenberg (2014) and an assumption of a mass

of $0.8 M_{\odot}$. The extinction was taken from Green et al. (2019) where available and Schlegel et al. (1998) otherwise. We measured the abundances of Mg and Fe through equivalent width analysis and of Na, Al, Mn, Ba, and Eu through spectral synthesis with hyperfine structure splitting included, and applied NLTE corrections of Lind et al. (2022) to the Na and Al abundances. We simply averaged the line-by-line abundances to obtain the final abundance of each element. We estimated the uncertainties from the sample standard deviation of the line-by-line abundances (σ) and the number of lines (N) as σ/\sqrt{N} when $N > 3$; otherwise, we replaced the σ with that of neutral iron. We additionally considered the uncertainties due to the stellar parameters. We report the measured abundances in Table A.1.

For the X-Shooter spectra, we initially stacked individual radial velocity-corrected exposures. We assumed atmospheric parameters from Andrae et al. (2023), with the exception of star 3757312745743087232, where *Gaia* XP spectra was used instead. We synthesised H α and H β NLTE line profiles using the tools provided by Kovalev et al. (2018). We find that the adopted values for T_{eff} and $\log(g)$ adequately reproduce the wings of the Balmer lines. The spectra for each star was normalised assuming a $[\text{Fe}/\text{H}] = -2.5$ template in the range between 330nm to 1100nm. Finally, while keeping the atmospheric parameters constant we derived Fe abundances using the SYNTHE transfer code (Sbordone et al. 2004), assuming the ATLAS 9 models (Kurucz 2005), and atomic data from Kupka et al. (2011). We did so by minimising the χ^2 between observed and synthetic fluxes around a set of selected Fe features. We report the Fe abundances and their associated uncertainties in Table A.2.

Table A.1. Stellar parameters and chemical abundances for ED-2 stars.

<code>source_id</code>	T_{eff} [K]	$\log g$ –	v_t [km s ⁻¹]	$[\text{Fe}/\text{H}]_{\text{I}}$ –	$[\text{Fe}/\text{H}]_{\text{II}}$ –	$[\text{Na}/\text{Fe}]$ –	$[\text{Mg}/\text{Fe}]$ –	$[\text{Al}/\text{Fe}]$ –	$[\text{Mn}/\text{Fe}]$ –	$[\text{Ba}/\text{Fe}]$ –	$[\text{Eu}/\text{Fe}]$ –
4245522468554091904	6657	4.30	1.68	-2.48 ± 0.05	-2.46 ± 0.10	-0.25 ± 0.10	0.18 ± 0.07	-0.22 ± 0.07	-0.45 ± 0.12	-0.13 ± 0.15	
4479226310758314496	5974	4.53	1.12	-2.70 ± 0.05	-2.57 ± 0.06	-0.23 ± 0.07	0.30 ± 0.08	-0.34 ± 0.07	-0.52 ± 0.09	-0.35 ± 0.10	
6632335060231088896	5620	3.60	1.32	-2.54 ± 0.05	-2.44 ± 0.04	-0.07 ± 0.08	0.33 ± 0.06	-0.32 ± 0.07	-0.41 ± 0.06	-0.17 ± 0.08	0.61 ± 0.08
6746114585056265600	6110	4.55	1.28	-2.57 ± 0.05	-2.44 ± 0.02	-0.25 ± 0.08	0.29 ± 0.06	-0.27 ± 0.08	-0.43 ± 0.06	-0.24 ± 0.09	
4318465066420528000^a	5445	3.04	1.60	-2.33 ± 0.05	-2.35 ± 0.05	-0.15 ± 0.09	0.38 ± 0.04	-0.17 ± 0.09	-0.14 ± 0.10	-0.04 ± 0.10	0.58 ± 0.10
4318465066420528000^{a*}	5211	2.93	1.19	-2.56 ± 0.12	-2.49 ± 0.12		0.48 ± 0.05			0.11 ± 0.13	0.52 ± 0.05

Notes. The three ED-2 stars in our UVES programme, supplemented by an ED-2 star from the ESO archive (second entry) are shown in the first part. The bottom two entries correspond to the binary star of *Gaia* BH3, as estimated following the procedure described in this paper and as presented in Gaia Collaboration (2024), respectively. ^aThe difference T_{eff} between the two studies is due to different extinction maps used and is responsible for the relatively large difference in $[\text{Fe}/\text{H}]_{\text{I}}$. The differences in the other ratios are likely due to systematic errors that are not accounted for in the quoted uncertainties, as the abundance ratios are rather insensitive to the choice of T_{eff} . Sources for such systematic uncertainties include the use of different linelists, radiative transfer codes, and atmospheric models.

Table A.2. Stellar parameters and $[\text{Fe}/\text{H}]$ for the X-Shooter sample.

<code>source_id</code>	T_{eff} [K]	$\log g$ –	$[\text{Fe}/\text{H}]_{\text{I}}$ –
3549718318990080896	5319	3.3	-2.52 ± 0.08
3869876996687740032*	5372	3.4	-2.50 ± 0.10
6747065215934660608	5535	4.3	-2.53 ± 0.08
6646097819069706624	5653	4.4	-2.54 ± 0.10
3473979147705211776	5733	4.4	-2.57 ± 0.14
3757312745743087232	6591	4.2	-2.23 ± 0.41

Notes. The reported T_{eff} and $\log g$ are from Andrae et al. (2023), except for star `source_id` 3757312745743087232 where the atmospheric parameters were inferred from the *Gaia* XP spectra. An asterisk (*) after the `source_id` flags stars not originally in Dodd et al. (2023).