An X-ray-quiet black hole born with a negligible kick in a massive binary within the Large Magellanic Cloud

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Stellar-mass black holes are the final remnants of stars born with more than 15 solar masses. Billions are expected to reside in the Local Group, yet only a few are known, mostly detected through X-rays emitted as they accrete material from a companion star. Here, we report on VFTS 243: a massive X-ray-faint binary in the Large Magellanic Cloud. With an orbital period of 10.4 d, it comprises an O-type star of 25 solar masses and an unseen companion of at least nine solar masses. Our spectral analysis excludes a non-degenerate companion at a 5σ confidence level. The minimum companion mass implies that it is a black hole. No other X-ray-quiet black hole is unambiguously known outside our Galaxy. The (near-)circular orbit and kinematics of VFTS 243 imply that the collapse of the progenitor into a black hole was associated with little or no ejected material or black-hole kick. Identifying such unique binaries substantially impacts the predicted rates of gravitational-wave detections and properties of core-collapse supernovae across the cosmos.

Pairs of stellar-mass black holes in the distant Universe occasionally merge, unleashing bursts of gravitational waves that can be detected here on Earth. The number of recorded merger events since their detection in 2015 is approaching the 100 mark, and is expected to grow by orders of magnitude in the coming years. In this context, there is an overwhelming international effort aimed at understanding the evolutionary pathways of the merging black holes and the massive stars that formed them. A fundamental uncertainty in this endeavour is whether, and under what conditions, black-hole progenitors experience supernova explosions and kicks during core collapse. This question has far-reaching consequences: from the observed supernova types and their distributions, through the retention of black holes in globular clusters, to the survivability of black-hole binaries in the context of gravitational-wave production and detection rates. Empirical data on the question of kicks are sparse, largely model dependent and point in conflicting directions.

Constraints on supernova kicks originate primarily in X-ray binaries containing a black hole. By construction, black-hole X-ray binaries consist of a donor star that transfers mass onto an accretor star, therefore indispensable laboratories to tackle the question of kicks empirically. Such binaries preserve the black-hole kick signatures

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in their orbit. Of special interest are massive (O- and early B-type) binaries hosting black holes (OB+BH), which represent a key evolutionary phase towards black-hole mergers. The few known X-ray bright OB+BH binaries are thought to constitute the ‘tip of the iceberg’: hundreds of X-ray-quiet counterparts are predicted to reside in the Milky Way and the Magellanic Clouds. However, we remain blind to this elusive population of binaries. Only a few low-mass binaries with black-hole companions have been reported in the past. In recent years, multiple claims for massive OB+BH binaries in the Milky Way and the Large Magellanic Cloud (LMC) have emerged. However, virtually all of these reports have been challenged or refuted by follow-up studies. Aside from a few candidates that require confirmation, massive X-ray-quiet OB+BH binaries are not known anywhere, let alone outside our Galaxy.

Here, we report on the unambiguous discovery of an extragalactic X-ray-quiescent O+BH binary, VFTS 243. Located in the Tarantula nebula in the subsolar metallicity environment ($Z \approx 0.5Z_{\odot}$) of the LMC, VFTS 243 is one of 51 O-type single-lined spectroscopic binaries (SB1s) characterized by the Tarantula Massive Binary Monitoring (TMBM). These SB1 binaries each comprise a well identified massive O-type star orbiting a ‘hidden’ companion whose spectral signature has not been detected so far. Using a state-of-the-art analysis method described below, we could unveil the spectral signatures of non-degenerate companions in the vast majority of the 51 SB1 binaries (T.S. et al., manuscript in preparation), but not in VFTS 243. VFTS 243 is the sole target in the sample for which a black-hole companion provides the only solution consistent with the data. We show this below.

**Results**

We analyse multi-epoch optical spectroscopy acquired with the Fibre Large Array Multi Element Spectrograph (FLAMES) of the European Southern Observatory (ESO) in GIRAFFE mode. Our data cover about six years of observations and consist of five epochs from the Very Large Telescope FLAMES Tarantula Survey (VFTS), obtained in 2008 and 2009, and an additional 32 epochs from TMBM obtained between 2012 and 2014. The spectra cover the wavelength range 3,964–4,567 Å at a resolving power of $R = 6,400$ and sampling of $\Delta \lambda = 0.2$ Å, and have a median signal-to-noise ratio.
Table 1 | Derived parameters for VFTS 243

| Parameter          | Value                  |
|--------------------|------------------------|
| \( P [d] \)        | 10.4031 ± 0.0004       |
| \( T_0 \) [JD − 2,400,000] | 54,870.7 ± 1.5        |
| \( e \)            | 0.017 ± 0.012          |
| \( \omega [\text{s}^\circ] \) | 66 ± 53               |
| \( K_1 [\text{km s}^{-1}] \) | 81.4 ± 1.3            |
| \( \Gamma [\text{km s}^{-1}] \) | 260.2 ± 0.9           |
| \( f [M_{\odot}] \)  | 0.581 ± 0.028         |
| \( T_{\text{eff},1} \) [KK] | 36 ± 1                |
| \( \log g_1 [\text{cgs}] \) | 3.7 ± 0.1             |
| \( E_V [\text{mag}] \)  | 0.45 ± 0.02           |
| \( A_V [\text{mag}] \)  | 1.76 ± 0.08           |
| \( \log M/\sqrt{D} [M_{\odot} \text{yr}^{-1}] \) | −6.3 ± 0.3            |
| \( v_w [\text{km s}^{-1}] \) (adopted) | 2,100                 |
| \( X_\text{H} [%] \) | 0.11 ± 0.05           |
| \( X_\text{He} / X_{\text{He,LMC}} \) | 16 ± 7                |
| \( A_\nu [\text{mag}] \)  | 1.70 ± 0.03           |
| \( \log L_1 (L_{\odot}) \) | 5.20 ± 0.04           |
| \( R_1 (R_{\odot}) \) | 10.3 ± 0.8            |
| \( R_1 / R_{\text{Roche,least}} \) | 0.33 ± 0.03           |
| \( v \sin i [\text{km s}^{-1}] \) | 181 ± 16              |
| \( M_{\text{He}} [M_{\odot}] \) | 25.9 ± 3.1            |
| \( M_{\text{tot}} [M_{\odot}] \) | 26.2 ± 2.1            |
| \( M_{\text{spec},1} [M_{\odot}] \) | 19.3 ± 5.2            |
| \( M_2 [M_{\odot}] \) | 25.0 ± 2.3            |
| \( M_{\text{He,2}} [M_{\odot}] \) | 8.7 ± 0.5             |
| \( M_{\text{He,2}} [M_{\odot}] \) | 10.1 ± 2.0            |
| \( M_{\text{He,2}} [M_{\odot}] \) | 36.3 ± 3.8            |
| \( i [\text{\degree}] \) | ≥ 40                  |
| \( \text{Age} [\text{Myr}] \) | 7.4                   |

Values related to the primary O7 V component are marked with '1', those related to the hidden secondary component with '2'. Errors correspond to 68% confidence intervals (asymmetric errors are rounded off when differences are small). In addition to the parameters introduced in the text, we also list the argument of periastron (\( \omega \)), the systemic radial velocity (\( \Gamma \)), the colour excess (\( E_V \)), and extinction \( A_V \). The Roche-lobe filling factor \( R_1 / R_{\text{Roche,least}} \), the terminal velocity \( v_w \), and clumping-uncorrected mass loss rate \( M v_w \sqrt{D} \) (where \( D \) is the clumping factor) and the nitrogen mass fraction \( X_\text{N} \) (remaining abundances are set to baseline). \( i_\text{obs} \) is the orbital inclination of the binary plane measured from the line of nodes, and assuming \( i_\text{obs} = 90^\circ \) for the secondary stellar component. All estimates yield consistent results within their respective 1σ errors (Table 1). The weighted mean is \( M_1 = 25.0 ± 2.3 M_{\odot} \). The binary mass function and primary mass yield a minimum mass of the hidden companion (that is, at an inclination of \( i = 90^\circ \)) of \( M_{\text{min}} = 8.7 ± 0.5 M_{\odot} \), with a 99.7% confidence interval of 7.2–10.1 \( M_{\odot} \). By modelling the probability density of \( M_2 \), as a Gaussian with a mean of 25.0 \( M_{\odot} \) and \( \sigma = 2.3 M_{\odot} \), and assuming a random orientation of the orbital plane (amounting to a probability distribution of the orbital inclination of \( P(i) = \sin i \)), we derive the posterior of \( M_2 \) via a Monte Carlo simulation. The posterior has a median and 68% confidence interval of \( M_2 = 10.1 ± 2.1 M_{\odot} \), with a mode of 9.0 \( M_{\odot} \). Similarly, the total mass has a median and 68% confidence interval of \( M_{\text{tot}} = 36.3 ± 3.8 M_{\odot} \), and a mode of 35.0 \( M_{\odot} \). The faint ellipsoidal variations detected in the light curve of VFTS 243 are consistent with our mass estimates, and imply an orbital inclination of the range 40–90° (Supplementary Information).

A main-sequence companion accommodating the constraint on \( M_{\text{spec},1} \) would need to have a spectral type earlier than \( \sim B3 \) V. More exotic and much less likely than a black hole, the hidden companion may be a massive helium star or a binary itself. Should any of these scenarios be viable, the spectral signature of the companion(s) would have been identified by grid spectral disentangling. This technique exploits the Doppler motion of the binary components to extract their individual component spectra (Methods). Thanks to the substantial enhancement of the S/N that results from combining the entire dataset, the spectral disentangling technique allows us to uncover spectral signatures of objects contributing as little as \( \sim 1\% \) to the optical flux. It has further been successfully applied in the past to unveil the hidden companion stars in other binaries erroneously identified as black-hole binaries (for example, LB-118, HR 6819\textsuperscript{21}, 2M0412\textsuperscript{22}). Fixing the orbital period and eccentricity, we varied \( K_1 \) and \( K_2 \) by minimizing the reduced chi-square statistic \( \chi^2_{\text{red}}(K_1, K_2) \) between the co-added disentangled spectra and each observation. We find that \( \chi^2 \) is flat with respect to \( K_2 \), implying that...
the quality of agreement is independent of $K_\gamma$ (Fig. 3). Regardless of the input value of $K_\gamma$, the extracted spectrum of the secondary is virtually flat, and does not contain features that can be considered of stellar origin (Fig. 4). Hence, the companion is either an optically faint non-degenerate star (or binary) or a compact object.

To test whether a faint non-degenerate companion could have avoided detection, we produce mock data mimicking the phase coverage and data quality (that is, S/N, resolving power) of the real data. We consider companions as light as $M_\ast \approx 4 M_\odot$ (well below our 5σ threshold), contributing as little as ~1% to the total flux. We perform simulations by combining spectral templates and synthetic noise, as well as by injecting spectral templates and additional noise into the real data. In all simulated cases, the grid disentangling method is able to retrieve the signature of the hypothesized companion without ambiguity, whether it is a main-sequence dwarf, a helium star or a binary itself (Fig. 5). This shows that, if it was present in VFTS 243, a non-degenerate companion would have been identified. Having rejected all other scenarios, we are left to conclude that the hidden companion is a stellar-mass black hole. No other X-ray-quiet OB+BH binaries have been unambiguously detected outside our Galaxy so far.

**Discussion**

With more than ten refuted claims of X-ray-quiescent black-hole binaries in the last two years, it may be wondered whether VFTS 243 constitutes yet another false alarm. In this context, it is important to highlight the differences between VFTS 243 and the bulk of previously reported objects.

First, unlike the majority of previously reported X-ray-quiescent OB+BH binaries, whose analysis relied on interpretation of complex, near-static spectral emission lines, VFTS 243 exhibits a regular O-type star spectrum with no remarkable features. The orbital and spectral analysis, the disentangling of the system and the interpretation of the results are therefore straightforward and leave little room for complex scenarios.

Second, one of the major culprits of previous erroneous OB+BH claims was that the optically bright primaries in these binaries turned out to be rare, low-mass ($M \leq 2 M_\odot$), bloated stars that had been stripped of their outer envelopes. This led to a severe overestimation of the mass of the bright component, and, in turn, to a false report of black holes. Some of these scenarios further required low orbital inclinations, which are less likely from a statistical point of view. In contrast, our analysis leaves no room for the primary being a low-mass bloated stripped star, and the interpretation of the data does not hinge on an unlikely inclination, but rather points to inclinations larger than ~40°. In fact, even if the primary mass were to be overestimated, the ellipsoidal variability would require a very massive secondary component ($M_2 \geq 15 M_\odot$), which could only be explained if it were a black hole (Supplementary Information).

Finally, while X-ray-quiescent OB+BH binaries are very rare, uncovering them in a sample of 51 SB1 massive binaries is not surprising. Recent predictions suggest that roughly 8% of the 51 SB1 binaries in our sample should host black holes, amounting to four expected OB+BH targets in the TMBM SB1 sample.

Not only is VFTS 243 an OB+BH binary, but it is also an X-ray-faint one. Analysis of deep Chandra observations taken in the context of the Chandra Visionary Program T-ReX yields an X-ray-faint one. Analysis of deep Chandra observations taken in the context of the Chandra Visionary Program T-ReX yields an upper limit of $L_X < 32.16 \text{[erg s}^{-1}]$ on the intrinsic X-ray luminosity. Using the derived system parameters and unclumped wind mass loss rate (compare Table 1), we expect a Bondi–Hoyle wind accretion rate of $1.7 \times 10^{-11} M_\odot \text{yr}^{-1}$ (ref. 30). However, a necessary (yet not sufficient: see, for example, ref. 31) condition for producing copious X-rays is the formation of an accretion disk. Following ref. 33, we find the matter accreted by the BH to have about 30 times too little angular momentum to form an accretion disk. The infalling material is therefore not expected to radiate sufficiently to exceed the detectability threshold (Supplementary Information).

The relatively rapid rotation and CNO-processed material observed in the O7 V primary suggests that it has previously accreted mass from the black-hole progenitor. Such a process tends to circularize the binary orbit before the mass donor undergoes core collapse. It is therefore likely that the binary orbit had been circular before the core collapse of the black-hole progenitor. In the future, the system will probably experience a second mass-transfer phase as the O7 V star expands to fill its Roche lobe. The mass ratio of about 2.5 implies that the binary will tighten, and the properties of VFTS 243 suggest that it will end its life as a double black-hole binary within about 5 Myr. With an expected period of the order of a few days, this newly formed BH+BH binary should merge on a timescale of tens to a few hundreds of billion years.

The near-circular orbit of VFTS 243 ($e < 0.029$; 68% confidence interval) has important implications regarding core-collapse physics of black-hole progenitors. Since the rotation period is not synchronized with the orbit, tidal circularization can be neglected, implying that the current eccentricity has not changed since the formation of the system.
black hole formed (Supplementary Information). A mass loss $\Delta M$ during core collapse would have induced a change in eccentricity of $\Delta e = e - e_{\text{init}}$ of the order of $\Delta M = 0.2 - 0.5 M_\odot$ (ref. 19). Hence, we can conclude that no more than $\sim 0.5 M_\odot$ of the envelope of the star was removed during the core collapse associated with the formation of the black hole in VFTS 243.

Small mass loss and associated kicks were also proposed for the black-hole progenitor in the prototypical Galactic high-mass X-ray binary Cyg X-1 (ref. 20). However, the latter analysis invokes a diverse set of assumptions involving its origin in the Cygnus OB association and its present-day mass (which has been recently revised 21). Direct core collapse of black-hole progenitors is currently favoured by models for stars initially more massive than $\sim 20 M_\odot$ (ref. 22). However, indirect empirical evidence for supernovae and/or kicks associated with black holes have also been put forward 23. In this context, the properties of VFTS 243 provide direct empirical evidence for the implosion of a massive star into a black hole, and this at subsolar metallicity. Moreover, the $\sim 10 M_\odot$ black hole in VFTS 243 probes a mass regime where supernovae may be expected to occur 24.

VFTS 243 probably represents a glimpse of a much larger population of black-hole binaries to be detected in the coming years. Upcoming high-precision astrometry of binary systems from the European Space Agency (ESA) Gaia satellite 25 is predicted to reveal hundreds of such objects in our Galaxy 26,27, while future large-scale spectroscopic surveys (for example, SDSS/APOGEE, 4MOST) combined with photometric surveys (OGLE, TESS) 28 will enable astronomers to filter out additional extragalactic black-hole binaries. These upcoming samples should reveal whether the current properties of VFTS 243 are universally shared among OB + BH binaries. In turn, this will allow astronomers to learn whether core-collapse physics leading to black-hole formation is unique, or whether there is a diversity of pathways, possibly involving parameters such as stellar mass, rotation and metallicity. Answering these questions is important if we are to properly predict the properties of newly formed BH + BH binaries and adequately interpret the vast number of detections that will be provided by the next generation of gravitational-wave observatories.

Methods

Data. Our analysis mainly relies on 32 epochs of optical spectra acquired by the TMBM campaign 24 between Oct 2012 and Mar 2014 using the fibre-fed multi-object FLAMES mounted on UT2 of the Very Large Telescope (VLT) at Paranal observatory, Chile. The spectra cover the wavelength range 3,964–4,567 Å at a resolving power of $R = 6,400$, with a median S/N of 61. Five additional spectra from the VFTS campaign 29 with similar properties are also used. We extend this range with VFTS spectra covering the 4,499–5,071 Å and 6,442–6,817 Å ranges of similar resolution and S/N. In addition, we make use of a light curve of VFTS 243 obtained from the OGLE data reductions III and IV (ref. 26), as well as a compilation of photometry covering the UV–IR range.

Primary mass. We provide three mass estimates for the primary star in Table 1. (1) $M_{\text{init}}$ is obtained by computing the mean and s.d. of the evolutionary masses for stars initially more massive than $\sim 20 M_\odot$ (ref. 20). (2) $M_{\text{fwd}}$ is obtained by computing the mean and s.d. of the evolutionary masses for stars initially more massive than $\sim 20 M_\odot$ (ref. 20). (3) $M_{\text{fwd}}$ is obtained by computing the mean and s.d. of the evolutionary masses for stars initially more massive than $\sim 20 M_\odot$.
is, 0.65 V–0.75 V). The masses of these 19 stars were computed in ref. 12 using their measured physical properties (for example, \( L, T_\text{eff}, g \)) as input in the BonnSAI Bayesian tool (www.astro.uni-bonn.de/stars/bonnSai2), which estimates the evolutionary mass of single-star evolution tracks from refs. 13 and 14. \( M_\text{19} \) is obtained by inputting our derived values of \( L_\text{19} \) and \( T_\text{eff,19} \) for VFTS 243 in the BonnSAI tool. (3) \( M_\text{sec,10} \) is obtained via the surface gravity and stellar radius derived from spectroscopy. The stellar parameters and abundances are derived from a spectroscopic analysis. For this, we use the CMFGEN model atmosphere code15,16, through we perform the same analysis with two independent codes to explore systematics. The spectral analysis is provided in Supplementary Information.

All mass estimates agree within 1% per component. The final adopted value of \( M_1 \) is a weighted mean of \( M_{\text{freq}} \) and \( M_{\text{sec}} \) (we omit \( M_{\text{freq}} \) since it is not independent of \( M_1 \), being a mean of evolutionary masses). We note that the evolutionary masses are derived assuming single-star evolution models, while the properties of VFTS 243 suggest that the primary mass is derived from the tidal interaction. The reaction of the star to the mass accretion is not trivial, but may result in a slightly different mass–luminosity relation compared with single stars. Another factor we neglect is the impact of rotation and microturbulence pressure on the derivation of the surface gravity, which should result in a slight underestimation of the true log (by \( \approx 0.1 \text{dex} \)). Instead of adopting a series of non-trivial assumptions, we consider a very generous error margin of 5% per component in continuum regions48,49.

Photometric variability. The light curve of VFTS 243 contains evidence of both short- and long-timescale variability, though the long-term variability does not appear to be of stellar origin and is removed from the data. A Fourier analysis of the 1-band light curve shows a peak at a period of \( 5 \pm 1 \) d, which coincides exactly with half the spectroscopic orbital period. The phased light curve shows a modulation consistent with the presence of ellipsoidal variations, with \( A_{\text{ellip,sec}} = 0.0013 \pm 0.0003 \). The ellipsoidal variability amplitude at fixed period depends primarily on the density of the tidally distorted O star (hence \( M_1 \), \( R_1 \)) and on the secondary with weaker dependency on \( M_2 \) and \( R_2 \). To explore the range of binary parameters that can match the observed amplitude, we calculate a set of model light curves of binaries satisfying the orbital constraints that compromise a dark companion and an O star radius of 10.5 \( R_\odot \) using the PHOEBE tool17.

Radial velocity and proper motion. Next to the vanishing eccentricity, another indication for lack of a supernova kick can be obtained from the relative motion of VFTS 243 with respect to its natal environment. The systemic velocity of VFTS 243 is derived from Gaia38. We computed the means of the two components of the proper motion vector (RA, dec.) of all stars within 4' of VFTS 243 whose parallaxes and proper motions are consistent with the LMC. Since the errors in this case are dominated by statistical errors, we simply assume that the RV dispersion reflects the dispersion in RA and dec. directions as well. We find \( \sigma_{\text{RA}} = 936 \pm 12 \text{ km s}^{-1} \) and \( \sigma_{\text{dec}} = 145 \pm 12 \text{ km s}^{-1} \), making it impossible to hide in the data unless it were a black hole. The light curve shows that the black-hole interpretation is inescapable, even in the extreme overestimation of the primary mass below the 5% threshold explored here.

Data availability

The VFTS and TMBM spectra are available in the ESO archives (archive.eso.org/cds.html). The input files of our stellar evolution model (Supplementary Information) are available at https://nesdoc.org/record/65146416. The OGLE light curve is available for download at https://cdsarc.u-strasbg.fr/ftp/vizier/submit/OGLE/VFTS243. Any other processed materials are available from the corresponding author upon reasonable request.

Code availability

The OGLE tool used for Fourier disentangling is available online (http://sail.zpf.fer.hr/dinary). The shift-and-add Python implementation used here is available from the corresponding author upon reasonable request. We refer the reader to the CMFGEN (http://kookaburra.phys.ttu.edu/hillier/web/CMFGEN.htm), a Python implementation of the CMFGEN tool that can be downloaded from the following link (http://www.astro.uni-bonn.de/stars/bonnSai2).
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Author contributions
T.S, H.S., L.M. and M.F developed the analysis methodology. T.S. identified the target, performed the disentangling and simulations, derived the radial velocities, analysed the spectrum with PoWR and wrote the manuscript. H.S. led the TMBM observing campaign, prepared the observations and, together with L.A.A., performed data reduction, variability and orbital analysis of the TMBM sample and contributed to the interpretation. L.M. analysed the spectrum with CMFGEN. K.E.-B. performed the light-curve analysis, investigated the spectra independently and produced mock simulations for blind testing. P.M. and N.L. contributed to the interpretation of the evolutionary status and X-ray properties of the system. C.H. analysed the spectrum with FASTWIND. M.F. performed an independent test with Fourier disentangling. K.S. contributed to the discussion of X-ray production. D.J.L. contributed to the assessment of the light ratios of hypothetical main-sequence stars and investigated the spectra independently. J.M.A. provided an independent measure of the stellar parameters and luminosity. P.M., A.P., F.R.N.S. and M.G. contributed to the computation of synchronization and circularization timescales. All other authors contributed to acquisition of the data and discussion of the results and commented on the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
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