The Historical X-ray Transient KY TrA in quiescence

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ABSTRACT

We present deep optical images of the *historical* X-ray Transient KY TrA in quiescence from which we confirm the identification of the counterpart reported by Murdin et al. and derive an improved position of $\alpha = 15$:28:16.97 and $\delta = -61$:52:57.8. In 2007 June we obtained *I*, *R* and *V* images, where the counterpart seems to be double indicating the presence of an interloper at $\sim$1.4 arcsec NW. After separating the contribution of KY TrA we calculate $I = 21.47 \pm 0.09$, $R = 22.3 \pm 0.1$ and $V = 23.6 \pm 0.1$. Similar brightness in the *I*-band was measured in 2004 May and 2010 June. Variability was analysed from series of images taken in 2004, spanning 0.6 h, and in two blocks of 6 h during 2007. We find that the target is not variable in any data set above the error levels $\sim$0.07 mags. The presence of the interloper might explain the non-detection of the classic ellipsoidal modulation; our data indicates that it contributes around half of the total flux, which would make a variation $<$0.15 mag not detectable. A single spectrum obtained in 2004 May shows the Hα emission characteristic of X-ray transients in quiescence with a full width at half-maximum FWHM $= 2700 \pm 280$ km s^{-1}. If the system follows the FWHM–K_2 correlation found by Casares, this would correspond to a velocity semi-amplitude of the donor star of $K_2 = 630 \pm 74$ km s^{-1}. Based on the outburst amplitude and colours of the optical counterpart in quiescence we derive a crude estimate of the orbital period of 8 h and an upper limit of 15 h which would lead to mass function estimates of $\approx$9 M$_\odot$ and $<$16 M$_\odot$, respectively.

Key words: binaries: close – stars: individual: KY TrA – X-rays: binaries.

1 INTRODUCTION

Low-mass X-ray binaries (LMXBs) are mass-exchange binaries that contain an accreting black hole or neutron star primary and a low-mass secondary star. Accretion takes place through an accretion disc which encircles the compact object and regulates the flow of material on to it making these objects the brightest X-ray sources in the sky. LMXBs provide an ideal playground for exploring the physics of compact objects yielding the confirmation of the existence of stellar mass black holes. Optical observations are crucial to prove this. By observing the radial velocity curve of the companion star, one can determine the mass function of the system, which represents a minimum mass for the accreting compact object. This experiment can be best applied to a subclass of LMXBs, the so called X-ray Transients (XTs), in which X-ray activity occurs only during well-defined outburst episodes. Between outbursts, the emission from the accretion flow fades to the point that the companion star is clearly visible and it is nearly undisturbed by irradiation;

hence it can be used to derive a dynamical mass for the compact object (e.g. Charles & Coe 2006).

The distribution of black hole masses can only be determined from the study of X-ray binaries (e.g. Casares 2007) and it is intricately related to the population and evolution of massive stars, the energetics and dynamics of supernova explosions, and the critical mass dividing neutron stars and black holes. Several attempts to extract statistical information from the observed mass distribution have been made (Bailyn et al. 1998; Özel et al. 2010; Farr et al. 2011; Kreidberg et al. 2012), however, the small number of black holes prevents us from extracting very compelling conclusions. About $\sim$10^8–10^9 stellar–mass black holes are believed to exist in the Galaxy (Brown & Bethe 1994) while $\sim$10^3–10^4 are expected to be members of XTs (White & van Paradijs 1996; Romani 1998; Yungelson et al. 2006). Unfortunately, only $\sim$20 black hole candidates have reliable dynamical mass determinations to date. In summary, it becomes necessary to increase the sample of black hole masses.

The best place to look for black holes are XTs, which are detected in outburst by X-ray all-sky monitors. This was the case of KY TrA, a *historical* X-ray transient discovered in 1974 by the *Ariel V* instruments (Pounds et al. 1974). After a short precursor,

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Table 1. Log of the observations.

Photometry:

Date	Exp. time (s)	ΔT (hr)	Filter	Telescope / Instrument
2004/05/16	300	0.6	I	ESO VLT U4 / FORS2
2007/06/16	600	6.3	I	ESO 3.6 m / EFOSC
2007/06/17	600	6.0	I	″
″	1000	-	R	″
″	1500	-	V	″
2010/06/03	80	-	I	ESO VLT U1 / FORS2
″	45	-	R	″
″	300	-	Hα	″
2015/01/18	500	-	I	SMARTS 1.3 m / ANDICAM
″	500	-	R	″
″	800	-	V	″

Spectroscopy:

Date	Exp. time (s)	Grism	Telescope / Instrument
2004/05/16	2000	GRIS-600RI	ESO VLT U4 / FORS2

KY TrA reached an outburst peak flux of 0.9 Crab in the 3–6 keV band, before decaying with an e-folding time of about two months (Kaluziensky et al. 1975). The source also showed a low-intensity outburst in 1990 which was significantly fainter than the discovery 1974 outburst (Barret et al. 1995). Six months later, an upper limit to the quiescent X-ray luminosity of ~ 2–10×10^{33} erg s^{-1} was derived. The ultrasoft X-ray spectrum seen by *Ariel V* and the hard tail observed by SIGMA (Barret et al. 1992) strongly suggests that KY TrA is a black hole candidate. The optical counterpart was identified 12 d after the X-ray maximum of the 1974 outburst at $B = 17.5$ (Murdin et al. 1977). Surprisingly, no further optical studies have been done since.

In this paper we present an optical study of the counterpart of the X-ray Transient KY TrA in quiescence to test its identification and obtain information about the donor star.

2 OBSERVATIONS

2.1 Photometry

The field of KY TrA was observed on UT 2004 May 16 with the ESO VLT U4 telescope at Paranal and the FOcal Reducer and low dispersion Spectrograph (FORS2). Seven 300 s exposures were obtained in Johnson I, spinning over 0.6 h. We also obtained series of 600 s images in I on UT 2007 Jun 16 and 17 on the 3.6 m telescope at La Silla Observatory, equipped with the ESO Faint Object Spectrograph and Camera (EFOSC). In the first night of this run the sky was partially covered by clouds and no calibrations or images in other filters than I were obtained. Fortunately, weather improved on Jun 17 and we could take also V and R images of KY TrA with 1500 s and 1000 s, respectively. Furthermore R, I and Hα images were taken on UT 2010 June 03 on the ESO VLT U1 telescope at Paranal and FORS2 using 80 s, 45 s and 400 s integration respectively in each band.

For calibration, we observed the field of KY TrA on UT 2015 Jan 18 with the 1.3 m SMARTS telescope at Cerro Tololo (Chile). We took V, R and I images with, respectively, 800, 500 and 500 s of exposure time. We observed also the Landolt field SA107 with 30 s integration in each of the three bands. An observing log is presented in Table 1.

All images were corrected for bias and flat-fielded in the standard way using IRAF. In particular the 2007 I-band frames were affected by fringing so these images were corrected using a *master flat*, i.e. the result of the median of a set of dithered exposures of our field. Point spread function (PSF) photometry was obtained with DAOPHOT II (Stetson 1987) whereas differential photometry of the 2004 and 2007 series were performed creating a photometric reference level, through an *ensemble* of isolated stars in the KY TrA field, following the technique described in Honeycutt (1992).

We finally calibrated a set of stars in the 2015 field that we then used as secondary standards to calibrate the 2004 and 2007 images, taken under non-photometric conditions. To do so, we used the observatory extinction coefficients together with the zero-points extracted from the Landolt standards.

2.2 Spectroscopy

A single 2000 s spectrum was obtained on the night of 2004 May 16 using FORS2 at the ESO VLT U4 telescope at Paranal. We used the GRIS-600RI grism, and a 2×2 binning in both the spatial and spectral direction, which provides a wavelength coverage of $\lambda\lambda 5200$–8400 at 1.68 Å pix^{-1} dispersion and 600 km s^{-1} resolution. Standard procedures were used to de-bias and flat-field the spectra. The one-dimensional spectra were extracted using optimal extraction routines which maximize the final signal-to-noise ratio. A Hg–Cd–Ar–Ne arc was obtained to provide the wavelength calibration scale.

3 ASTROMETRY OF KY TRA

The optical counterpart of KY TrA was identified at $\alpha = 15{:}28{:}16.59$ and $\delta = -61{:}52{:}58.1$ (2000) by Murdin et al. (1977) 12 d after the outburst. These authors showed a Schmidt plate of the proposed counterpart but no deep image with the target in quiescence has been published to date. In Fig. 1 we show an improved finding chart of KY TrA (I-band, 1800 s exposure and 0.9 arcsec seeing, taken on 2007 June 17). The field is 2×2 arcmin and the star at the position proposed by Murdin et al. (1977) is marked in the centre. For comparison we have also marked the star labeled as 'S' in that paper. In this figure, we also show a zoom of the central region of 30×30 arcsec where an elongation of the source profile along the NW direction is clearly visible. We measure an elongation coefficient (the IRAF 'ellipsoidal' parameter) of 0.68, significantly larger than the typical values obtained for nearby field stars (0.32). Although this requires confirmation through better seeing quality images, it strongly suggests that the counterpart is double and the transient is blended with an interloper.

To obtain a precise astrometric solution, we used the positions of the astrometric standards selected from the USNO-B1 astrometric catalogue[1] with a nominal 0.2 arcsec uncertainty. Hundreds of reference objects can be identified in our field from which we selected 392, discarding the stars with significant proper motions. The IRAF tasks ccmap/cctran were applied for the astrometric transformation of the images. Formal rms uncertainties of the astrometric fit for our images are $\lesssim 0.25$ arcsec in both right ascension and declination, which is compatible with the maximum catalog position uncertainty

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[1] USNO-B1 is currently incorporated into the Naval Observatory Merged Astrometric Data set (NOMAD) which combines astrometric and photometric information from Hipparcos, Tycho-2, UCAC, Yellow-Blue6, USNO-B, and the 2MASS, www.nofs.navy.mil/data/fchpix/
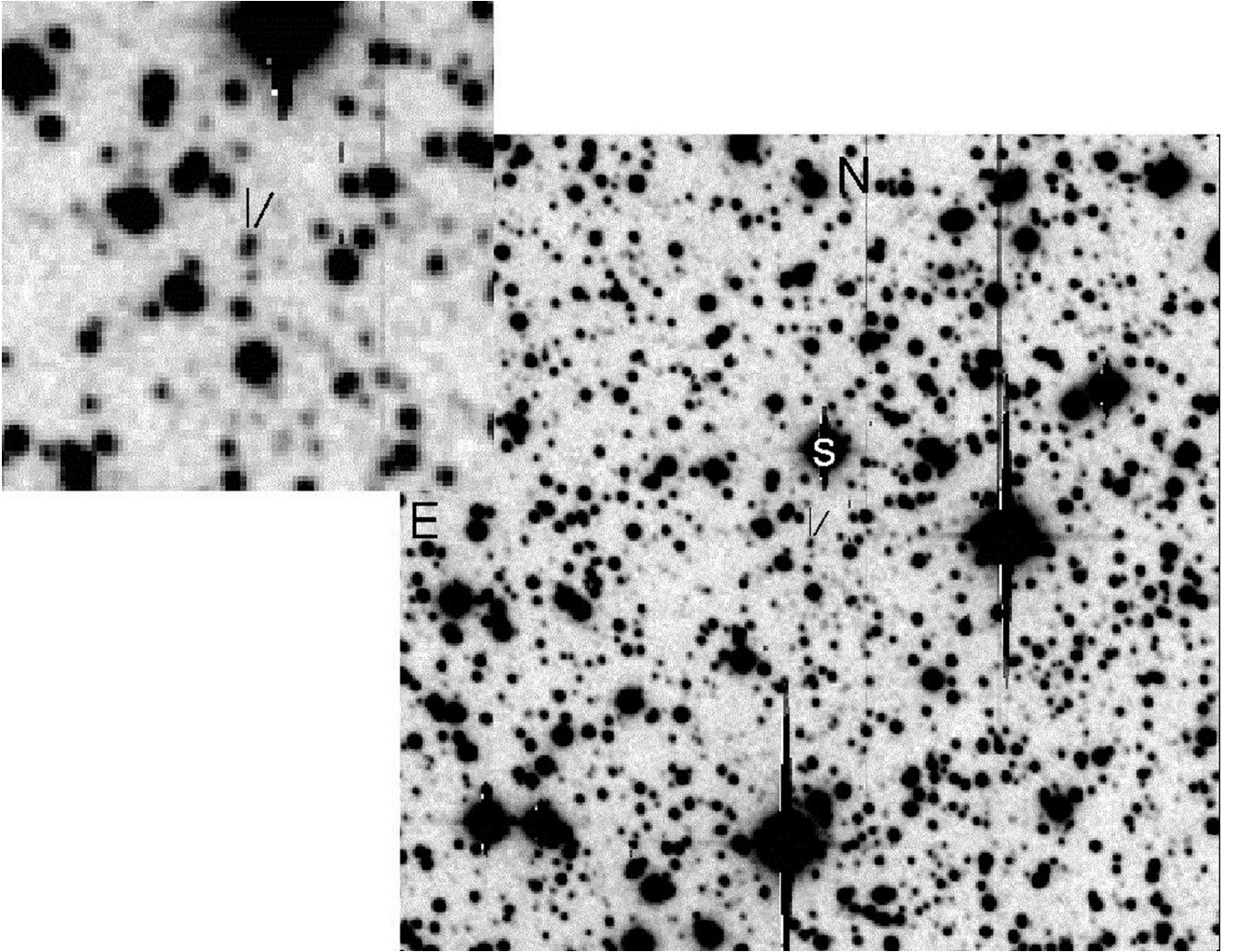
Figure 1. A 1800 s *I* image of KY TrA taken in 2007 June 17, with a field of view of 2×2 arcmin and a zoom of the central region of 30×30 arcsec. North is at the top, and East is to the left and the plate scale is 0.315 arcsec per pixel. Star labeling as 'S' in Murdin et al. (1977) is also shown for comparison. The target, in the middle of the fields, is marked. An elongation of the source profile along the NW direction is clearly visible indicating that the counterpart is double and it is blended with an interloper. The XT is the northern component of the pair (see Section 3).

of the selected standards. The star within the Murdin et al. (1977) error box has coordinates $\alpha = 15$:28:16.97 and $\delta = -61$:52:58.2 with a conservative estimate of our 3σ astrometric uncertainty of $\lesssim 0.3$ arcsec in both RA and Dec.

We test this identification by cross-matching the *R*, *I*, and Hα photometry of the field of KY TrA taken on 2010 to build the $(R-I)$–$(R-H\alpha)$ diagram of all the objects detected in the three photometric bands. Our proposed target (marked with a circle in Fig. 2) shows a clear Hα excess above the main stellar locus, confirming it is the true quiescent counterpart of KY TrA. Note that very close to the KT TrA counterpart there is another source of similar colour and Hα excess. This source is at 58 arcsec from the XT and its nature is unknown. However, KY TrA should be located even higher in this diagram since the presence of the interloper dilutes its actual Hα excess.

We can refine the location of the counterpart by choosing which of the components of the blend is actually the XT counterpart. To do so, we first aligned the *R*, *I*, and Hα images and then calculated the centroids of the profile targeted as KY TrA and of a set of 40 stars around it. In Fig. 3 (bottom) we show the modulus of the shifts between *R*, *I* and Hα, defined as $[(x_R - x_{H\alpha})^2 + (y_R - y_{H\alpha})^2]^{(1/2)}$

and $[(x_I - x_{H\alpha})^2 + (y_I - y_{H\alpha})^2]^{(1/2)}$ where (x, y) are the positions of the centroids in pixels. The centroid of KY TrA measured in Hα is clearly shifted with respect to its position in the *R* and *I* images. The top panel in Fig. 3 shows a zoom of the Hα image centred on our target, with the white cross marking its centroid and the black cross the centroid measured in the *I*-band image. This indicates that the XT is the component of the blend located at the NW. Assuming that the Hα centroid is the actual position of the target, we derived an improved source position of $\alpha = 15$:28:16.97 and $\delta = -61$:52:57.8 with an uncertainty of $\lesssim 0\rlap{.}''3$ arcsec in both RA and Dec.

4 PHOTOMETRY

4.1 The colours of ky tra

The colours of KY TrA in quiescence were obtained on UT 2007 June 17. We calculated $I = 20.88 \pm 0.01$, $R = 21.75 \pm 0.01$ and $V = 22.83 \pm 0.12$. Photometric error estimates on the magnitudes are based on a combination of Poisson statistics and the error contribution of the stars used for calibration. These magnitudes, however, correspond to the transient blended with the interloper
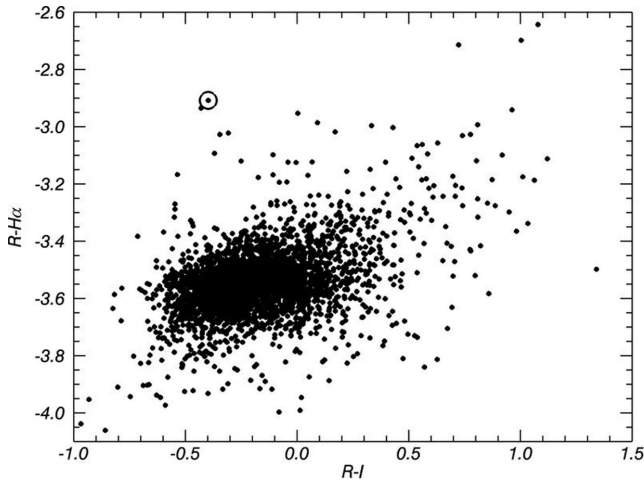
Figure 2. KY TrA uncalibrated $(R-I)$–$(R-H\alpha)$ diagram of all the objects detected in the three photometric bands in our field of view. Our proposed target, marked with a circle, shows a clear $H\alpha$ excess above the main stellar locus. Under the hypothesis that the light of KY TrA is contaminated by an interloper, it should be located even higher in this diagram, with a larger $H\alpha$ excess. The source closest to KY TrA is unknown.
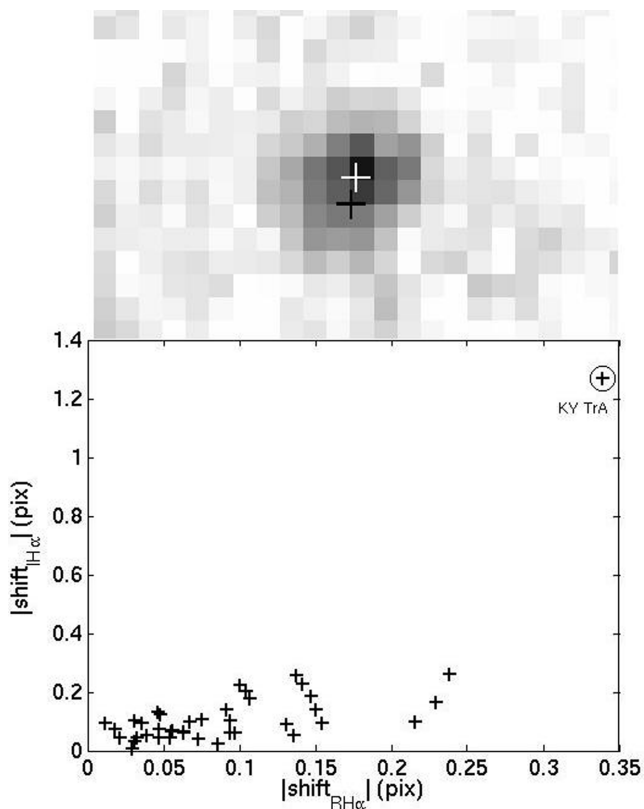

Figure 3. (Upper) Zoom of the $H\alpha$ profile of KY TrA with a white cross marking its centroid. The black cross marks the centroid measured in the I image. (Lower) Modulus of the shifts (in pixels) between the image centroid positions for KY TrA and 40 surrounding stars as measured in our R, I and $H\alpha$ images (for details see text).

(see Section 3) so they need to be corrected taking this into account. To do so, we cleaned the contribution of the contaminant component by subtracting its best PSF fit. The initial centres for fitting the profiles of the components were determined by visual inspection of the I image, where they are more clear. The two components of the blend have approximately equal brightness: we calculated $I = 21.47 \pm 0.09$, $R = 22.3 \pm 0.1$ and $V = 23.6 \pm 0.1$ for the top component, which is the XT counterpart as suggested by the $H\alpha$ image. The $(V - R)$ and $(V - I)$ colours are typical of a M0 star, although note that this is not corrected for interstellar reddening. Murdin et al. (1977) report a reddening $E(B - V) \geq 0.5$. An estimation of the interstellar reddening for any sky region can be obtained from the NASA/IPAC Infrared Science Archive.[2] The reddening quoted for the field of KY TrA, $E(B - V) = 0.7$, implies a corrected $(V - R)_0 = 0.77$ and $(V - I)_0 = 1.15$ consistent with an $\sim$K0−2V companion. Nevertheless, it should be noted that this is likely an upper limit to the true spectral type of the donor star because we have neglected any contribution from a residual accretion disc into the observed colour.

4.2 Searching for variability

The limited seeing conditions prevents us from deblending the flux of the two stars in every single image. Therefore, we studied the variability of KY TrA by integrating the total flux of the blend from the series of images in the I-band in the two different epochs: in 2004 May with less than one hour of observations and in 2007 June 16 and 17 with about 6 h coverage. The 2004 images were obtained during twilight so photometry accuracy was dominated by a bright sky level. Unfortunately, on 2007 June 16 we were affected by poor weather conditions with variable transparency caused by clouds. On 2007 June 17 no clouds were present although sky transparency was not ideal. In this night, we get $\sim$7 per cent photometry for a 21.5 magnitude star. In summary, we found that the target is not variable above the error levels in any of our nights (i.e. $\sigma = 0.07$, 0.14 and 0.07 mags for 2004 May and 2007 June 16 and 17, respectively). This is clearly seen in Fig. 4 where we plot the scatter in the observed magnitudes. The scatter around the mean magnitude of KY TrA (marked with a circle in Fig. 4) is consistent with that displayed by the field stars of similar mean brightness. Note that the presence of the interloper dilutes the orbital modulation of KY TrA, which would explain the lack of photometric variability on our images. Because the interloper contributes around half of the total flux, we can only conclude that the target is not variable by >0.15 mags.

After re-scaling the zero-point of each night we found that the total flux remains stable at $I = 20.88 \pm 0.01$ ($I = 21.47 \pm 0.09$ for KY TrA, i.e. the top component of the blend) in our entire data set, from 2004 until 2007.

5 SPECTROSCOPY

Although very noisy, our spectrum shows the $H\alpha$ emission line characteristic of X-ray transients in quiescence. We obtained its full width at half-maximum (FWHM) from a Gaussian fit of the continuum rectified spectrum within the range $\pm 10\,000$ km s^{-1}, centred on the $H\alpha$ line. This is shown in Fig. 5. After subtracting quadratically the instrumental resolution we find FWHM = 2700 ± 280 km s^{-1} where the error is the formal 1σ on the fitted parameter

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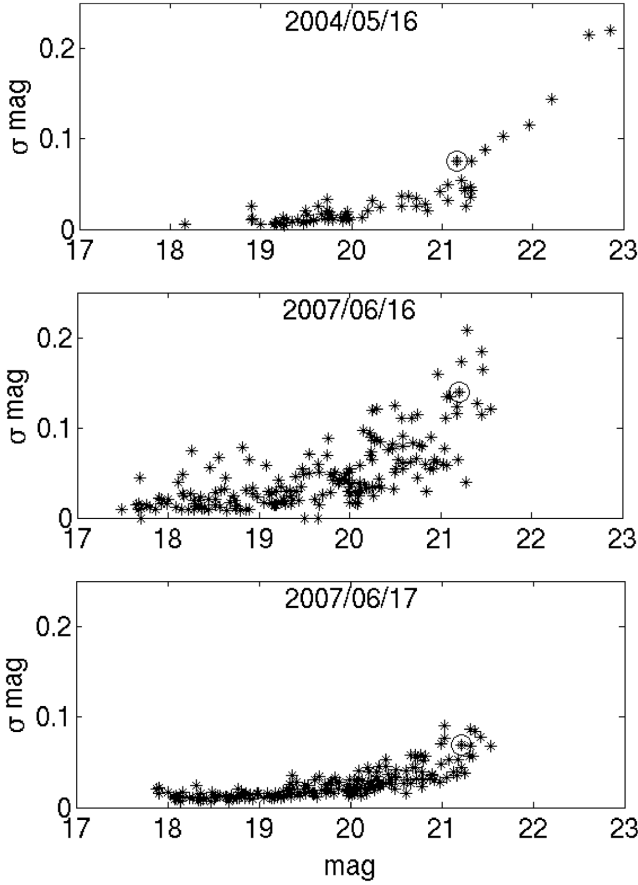[2] http://irsa.ipac.caltech.edu/applications/DUST/

Figure 4. Scatter of each individual star from its mean magnitude from the *I*-band series of images of each night. The blend (i.e, KY TrA plus the interloper) is marked with a circle.
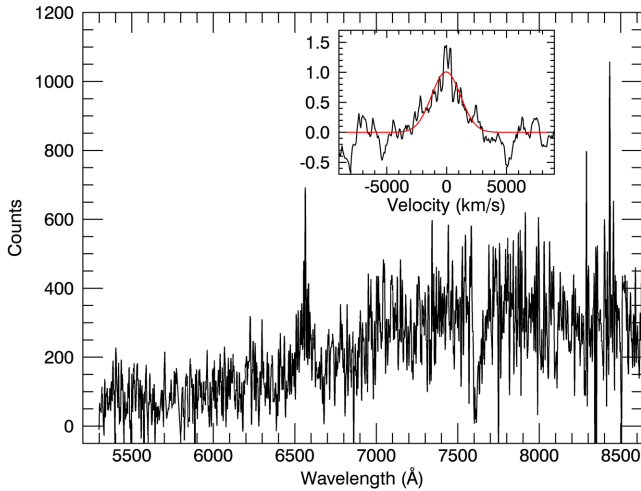

Figure 5. VLT optical spectrum of KY TrA from 2004 May 16, and (inset) a Gaussian fit to the Hα profile.

as derived through χ^2 minimization. We note that the quoted error is within the typical 10 per cent standard deviation caused by intrinsic line variability and therefore we take this as realistic (Casares 2015). We also extracted the equivalent width (EW) by integrating the Hα flux after continuum normalization and find EW = 72 ± 7 Å. Note, however, that this value is diluted by the extra continuum of the

interloper and hence the true EW of KY TrA is underestimated by a factor 2.

6 DISCUSSION

Although KY TrA is a very promising black hole candidate, it had not been studied in the optical band since its discovery in 1974. We have observed KY TrA in quiescence and confirmed its identification. The finding chart we present will certainly be helpful in performing observations with eELT-class telescopes in order to obtain dynamical information on the mass of the compact object.

A rough estimate of the period can be made by combining the Paczyński (1971) expression for the averaged radius of a Roche lobe with Kepler's Third Law to get the well-known relationship between the secondary's mean density and the orbital period: $\rho = (110/P_h^2)$ g cm^{-3}, where ρ is the mean density and P_h the orbital period in hours. Under the hypothesis that the light of KY TrA is contaminated by the interloper, we calculate an orbital period of about 8 h assuming a K0V star. It should be noted that this is likely an upper limit since, as we pointed out in Section 4.1, we have neglected any residual contribution from an accretion disc to the colour of KY TrA. An independent estimation can be made using the empirical relation $\Delta V = 14.36 - 7.63 \log P_h$ which predicts the orbital period of XTs with orbital periods less than 1 day given only its visual outburst amplitude ΔV (Shahbaz & Kuulkers 1998). During outburst, optical emission is dominated by the reprocessing of the X-rays in the accretion disc where most of the reprocessed energy is radiated in the ultraviolet. According to the irradiated model predictions $(B - V)^{disc} \sim 0$ (van Paradijs & McClintock 1995) resulting in $V \sim 17.5$ at the outburst peak (Murdin et al. 1977). Taking $V = 23.6$ in quiescence, the total outburst amplitude is ~ 6.1 mag so this would lead to an orbital period of about 12 h. We can place a robust upper limit for the period of about 15 h corresponding to a minimum outburst amplitude if the source were not contaminated by any interloper.

After analysing the Hα emission profiles of 12 dynamically confirmed black holes and 2 neutron star XTs in quiescence, Casares (2015) has found a tight correlation between the FWHM of the Hα line and the velocity semi-amplitude of the donor star, where $K_2 = 0.233(13) \times$ FWHM. We have applied this relation to KY TrA and predict $K_2 = 630 \pm 74$ km s^{-1}. This can be combined with our rough estimates of the orbital period to infer the mass function $f(M)$ of the binary. Our upper limit $P < 15$ h implies $f(M) < 16$ M$_\odot$ while $P \approx 8$ h would lead to $f(M) \approx 9$ M$_\odot$. More accurate constraints require an accurate determination of the orbital period.

Despite the foregoing, no variability has been found above the error levels, i.e. ~ 0.07 mags, indicating that we may be looking at the binary at very low inclination. However, given the contaminating flux from an interloper, the variability would be diluted to the extent that any intrinsic variability above ~ 0.15 mag would not be detectable given our error levels, and so the inclination might not be as low. Interestingly, KY TrA has one of the broadest Hα lines among SXTs (a summary of the parameters of the XTs can be found in Casares 2015 table 3), suggesting that, if KY TrA is viewed at low inclination, it must have a very short orbital period. Some clues about the inclination are provided by the EW of the Hα line, since it depends on the binary geometry. The EW tends to increase with inclination because, when the disc is seen at large inclinations, its continuum brightness decreases. An interesting exercise is to locate KY TrA in the EW–FWHM diagram shown in Fig. 5 of Casares (2015). Regions of constant inclination and M_1/P, where M_1 is the mass of the compact object and P is the orbital period, are defined in

the diagram. Both the relatively large EW and the high M_1/P factor are reminiscent of XTE J1118+480 and suggest that KY TrA also hosts a black hole seen at moderately high inclination. Furthermore, we point out that given the contaminating flux from an interloper, the observed EW would just be a lower limit to the true EW since the latter would be diluted by the excess continuum. Clearly, more higher quality photometry is necessary to resolve these issues and draw further firm conclusions.

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