A FWHM–$K_2$ CORRELATION IN BLACK HOLE TRANSIENTS

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ABSTRACT

We compare $H_\alpha$ emission profiles of 12 dynamically confirmed black holes (BHs) and 2 neutron star X-ray transients (SXTs) in quiescence with those of a sample of 43 Cataclysmic Variables (CVs), also quiescent. The FWHM of the $H_\alpha$ line in SXTs is tightly correlated with the velocity semi-amplitude of the donor star $K_2 = 0.233(13)$ FWHM. This new correlation, when combined with orbital periods (i.e., through photometric light curves), allows for the possibility of estimating compact object mass functions from single integration, low-resolution spectroscopy. On the other hand, CVs above the period gap are found to follow a flatter correlation, a likely consequence of their larger mass ratios. We also find that the FWHM traces the disk velocity at $\approx 10^3$ $R_{\rm L}$, independently of binary mass ratio. In addition, for a given FWHM, BHs tend to have lower EWs than CVs. This might be explained by the fact that CVs must be seen at higher inclinations to mimic the same projected disk velocities as BH SXTs. For the same reason, CVs with FWHM $\geq 1500$ km s$^{-1}$ are mostly eclipsing while none of our sample BHs are. Furthermore, we show that there is a vacant/unoccupied region for CVs in the FWHM–EW plane defined by FWHM $> 2568$ km s$^{-1}$ (km s$^{-1}$). Both the FWHM–$K_2$ correlation and the FWHM–EW plane can be exploited, together with photometric light curves, to efficiently discover quiescent BHs in deep $H_\alpha$ surveys of the Galactic plane.

Key words: accretion, accretion disks – binaries: close – novae, cataclysmic variables – stars: black holes – stars: dwarf novae – stars: neutron

1. INTRODUCTION

Black holes (BHs) provide unique laboratories to study key astrophysical phenomena such as accretion, the production of relativistic outflows, and gamma-ray bursts (e.g., Brown et al. 2000; Fender & Gallo 2014). BHs are usually discovered in transient X-ray binaries (soft X-ray transients; SXTs) thanks to their dramatic, large-amplitude X-ray outbursts. These are caused by thermal-viscous instabilities in accretion disks that are (slowly) fed by matter transferred from a (donor) companion star (Lasota 2001). The distribution of BH masses and binary periods provide fundamental constraints to models of supernovae explosions and compact binary evolution. Unfortunately, our understanding of the physics involved in these processes is still patchy because observational data are severely limited by small samples.

The current sample of $\sim 50$ BH SXTs, with only 17 dynamical confirmations, is the tip of the iceberg of a hidden population of hibernating BHs (see Casares & Jonker 2014). The size of the overall population is highly uncertain. Extrapolation of the number of SXTs discovered in the X-ray era suggests that several thousand dormant BHs are waiting to be discovered (van den Heuvel 1992; Tanaka & Shibazaki 1996; Romani 1998). On the other hand, modern population-synthesis models predict an even larger population of $\sim 10^4$–$10^5$ SXTs (Pfahl et al. 2003; Yungelson et al. 2006). Observational constraints are likely biased low because they suffer from incompleteness and neglect a hitherto unexpected population of long period SXTs with very long duty cycles or even supressed outburst activity (see Menou et al. 1999; Ritter & King 2002). Furthermore, there is mounting evidence for the existence of a population of X-ray obscured or intrinsically faint BH SXTs (Corral-Santana et al. 2013; Armas Padilla et al. 2014). It has been shown that the latter could be members of a sizeable population of short period BH transients with low outburst luminosities (Maccarone & Patruno 2013). Finally, the recent discovery of the first Be/BH binary indicates that some BHs might be accreting "silently" from the slowly outflowing winds of rapidly rotating Be-type stars (Casares et al. 2014). While binary population models predict a very modest number of Be/BH binaries in the Milky Way (Belczynski & Ziolkowski 2009; Grudzinska et al. 2015), empirical constraints, with only one detection yet, are very loose. Altogether, the only way to make significant progress in our knowledge of the Galactic population of BHs requires the discovery of a large sample of quiescent SXTs and this demands a new research methodology.

Quiescent BH SXTs are particularly difficult to find since they are relatively faint across the electromagnetic spectrum in this state. By their very nature, quiescent states are characterized by extremely low accretion levels ($< 10^{-9} M_\odot$ yr$^{-1}$). The inner disk is truncated in an advection dominated flow and, furthermore, the lack of a solid surface (an exclusive signature of BH) results in extremely weak X-ray, UV, and radio luminosities (Narayan & McClintock 2008; Miller-Jones et al. 2011). On the other hand, the optical spectrum is dominated by the low-mass donor star, with superposed emission lines from the accretion disk gas. The lack of a hard radiation field implies that only emission from neutral H and He is detected. Crucially, the strongest emission line is $H_\alpha$, but several other Galactic populations are also strong $H_\alpha$ emitters, such as cataclysmic variables (CVs), symbiotic binaries, flare stars, reddened Be stars, T Tauri, and other classes of young stellar objects. As a consequence, $H_\alpha$ surveys of the Galactic plane are vastly outnumbered by these populations of contaminating $H_\alpha$ emitters. Attempts to clear out the sample
using color selection cuts (Corral-Santana et al. 2008) or X-ray diagnostics (Jonker et al. 2011) still have to prove their effectiveness. Interestingly, new generation radio surveys (SKA and its pathfinders) may offer an alternative route to detect quiescent BHs given the increase in radio-to-X-ray flux ratios at very low luminosities (Maccarone 2005).

Here we present the discovery of a correlation between the width of the $H_\alpha$ line and the projected velocity of the companion star in quiescent SXTs. This property can be applied, in combination with photometric orbital periods, to gather compact object mass functions and flag new potential BHs. This strategy can be turned into a novel technique to unveil hibernating BHs, a technique that appears much more efficient than traditional methods based on time-consuming spectroscopic monitoring of new X-ray novae.

2. THE SAMPLE

2.1. X-Ray Transients

We have assembled a spectroscopic database of dynamically confirmed BH SXTs with $H_\alpha$ emission (see Table 1). Most spectra were collected by us (V404 Cyg, BW Cir, N Mus 91, GS 2000+25, A0620-00, XTE J1650-500, XTE J1859+226, GRO J0422+320, and XTE J1118+480) and have been presented in several publications, while others were kindly provided by J. Orosz (XTE J1550–564), R. Remillard (N Oph 77), and A. Fillipenko (N. Vel 93). In addition, three new unpublished spectra of GRO J0422+320 were obtained on the night of 2009 January 28 with ALFOSC on the 2.5 m Nordic Optical Telescope (NOT) at the Observatorio del Roque de los Muchachos. Integration time was set to 2400 s and we used grism #4 and a 1″ slit to cover the range of $\lambda\lambda$3820–9140 at 360 km s$^{-1}$ resolution. Seventy unpublished $H_\alpha$ spectra of V404 Cyg were also collected between 1994 and 2005 with the 2.5 m Isaac Newton Telescope (INT) and the 4.2 m William Herschel Telescope (WHT) at resolutions of 36–134 km s$^{-1}$. Five additional spectra of V404 Cyg were obtained on the nights of 2008 July 5, 7, and 8 at 200 km s$^{-1}$ resolution with the 2.1 m telescope at the Observatorio San Pedro Mártir (SPM). Finally, the sample also includes spectra of the two only neutron star SXTs with a reported radial velocity curve of the companion star, Cen X-4 and XTE J2123–058. Table 1 provides the main observational details and associated references for every system.

2.2. Cataclysmic Variables

We also collected a database of $H_\alpha$ spectra of CVs in quiescence including 41 dwarf novae and two intermediate polars, also classified as classical novae (GK Per and DQ Her). Most of the spectra were acquired during several observing campaigns and service nights performed with the WHT in 1992, 1993, 1998, and 2006, the INT in 1992, 2001, 2008, and 2009, the NOT telescope in 2008, 2009, and 2012, the 2.2 m telescope at the Calar Alto Observatory in 1995, and the 2.1 m telescope at SPM in 2008. The WHT spectra were obtained with ISIS and the R1200R grating, which delivers 40 km s$^{-1}$ resolution at $H_\alpha$. The INT spectra were obtained with the IDS spectrograph and gratings R150V, R300V, R900V, and R1200R covering the $H_\alpha$ region at 50–320 km s$^{-1}$ resolution. For the NOT campaigns we used ALFOSC and grism #7 with different slit widths providing 235–310 km s$^{-1}$ resolution. The Calar Alto data were collected with the CASSPEC spectrograph, the f3 camera and grating #11 in second order, which delivered 27 km s$^{-1}$ resolution. The SPM spectra were obtained with the Boller & Chivens spectrograph and a 600 l/mm grating to yield 192 km s$^{-1}$ resolution. Spectra of 13 CVs (BV Cen, EY Cyg, DX And, HS0218+3229, AH Her, HS2325+8205, SDSS J100658.40+233724, U Gem, CTV J1300–3052, OY Car, V2051 Oph, SDSS 103533.02+055158, and SDSS J143317.78+101123.3) were kindly provided by different authors while $H_\alpha$ parameters for other 15 CVs were compiled from the literature. In addition, spectra of WZ Sge were retrieved from the ING archive and reduced by us. The final collection of CV spectra were employed as a test sample for comparison with the $H_\alpha$ properties of SXTs. All of the CVs have secured velocity amplitudes ($K_2$) of their companion stars either through radial velocity studies or eclipse light curve solutions (for short period binaries where the companion star is undetected). Table 2 summarizes the main observational details of the CV database. The database is intended to be a representative sample of quiescent CVs with available $K_2$ determinations, though we warn about possible selection effects. These will be addressed in the following section.

3. THE FWHM–$K_2$ CORRELATION

FWHM values were obtained from Gaussian fits to individual $H_\alpha$ profiles in every SXT. The fitted model consists of a constant plus a Gaussian function. Continuum rectified spectra were fitted in a window of ±10,000 km s$^{-1}$, centered on the $H_\alpha$ line after masking the neighboring He I line at $\lambda$6678.

| Object | # Spectra | Year | Resolution (km s$^{-1}$) | References |
|--------|-----------|------|--------------------------|-------------|
| V404 Cyg | 266 | 1989–2009 | 6–180 | (1)–(8) |
| BW Cir | 96 | 1995–2006 | 70–110 | (9), (10) |
| XTE J1550–564 | 33 | 2001, 2008 | 55–165 | (11), (12) |
| N. Oph 77 | 1 | 1993 | 180 | (13) |
| N. Mus 91 | 29 | 1993–1995 | 74–90 | (14) |
| GS 2000+25 | 25 | 1995 | 196 | (15) |
| A0620–00 | 20 | 2000 | 7 | (16) |
| XTE J1650–500 | 15 | 2002 | 35 | (17) |
| N Vel 93 | 1 | 1998 | 120 | (18) |
| XTE J1859+226 | 10 | 2010 | 255 | (19) |
| GRO J0422+320 | 21 | 1994, 1995, 2000, 2008 | 230–630 | (8), (20) |
| XTE J1118+480 | 12 | 2011 | 120 | (21) |

| Neutron Stars | |
|----------------|-----------------|
| Cen X-4 | 90 | 1993–2002 | 6–74 | (22)–(24) |
| XTE J2123–058 | 20 | 2000 | 123–183 | (25) |

References: (1) Casares et al. (1991), (2) Casares & Charles (1992), (3) Casares et al. (1992), (4) Casares et al. (1993), (5) Casares & Charles (1994), (6) Hynes et al. (2002), (7) Gonzalez Hernandez et al. (2011), (8) this paper, (9) Casares et al. (2004), (10) Casares et al. (2009a), (11) Oroz et al. (2011), (12) Oroz et al. (2002), (13) Remillard et al. (1996), (14) Casares et al. (1997), (15) Casares et al. (1995a), (16) Gonzalez Hernandez & Casares (2010), (17) Oroz et al. (2004), (18) Fillipenko et al. (1999), (19) Corral-Santana et al. (2011), (20) Casares et al. (1995b), (21) Gonzalez Hernandez et al. (2012), (22) Torres et al. (2002), (23) D’Avenzo et al. (2005), (24) Casares et al. (2007), (25) Casares et al. (2002).
We adopted 1σ formal errors on the fitted parameter as derived through χ² minimization. Figure 1 displays some fit examples to average line profiles covering the entire range of line widths displayed by our data. It is clear from the figure that a simple Gaussian does not provide an accurate description of very broad profiles with large double peak separations. However, we find that the FWHM given by the Gaussian model is within 10% of other width parameters obtained from more sophisticated double-Gaussian models. More importantly, it is far more robust since double-Gaussian models can easily fail when fitting low signal-to-noise profiles. In addition to the FWHM, we also extracted EW by integrating the Hβ flux in individual spectra, after continuum normalization.

Our 266 spectra of V404 Cyg span over 20 years and, therefore, present the most complete database yet for the analysis of the secular evolution of accretion disks in quiescent BHs. Figure 2 presents the evolution of both line parameters, FWHM and EW, in V404 Cyg. The data points have been folded into 50-day bins, except for the first 30 days where 1-day bins were used to better trace the rapid evolution through the outburst. The plot shows a steep rise in FWHM (drop in EW) followed by a plateau phase starting ∼1300 days after the peak of the outburst. By taking the FWHM as a proxy of the disk radius, Figure 2 indicates that the accretion disk shrinks during outburst, recovering an equilibrium radius ∼3.5 years after the maximum. Evidence of accretion disk shrinkage following outburst has been reported for CVs using eclipse timing and eclipse mapping techniques (Smak 1984; Baptista & Catalán 2001). Because we are interested here in comparing average properties of stable quiescent disks in SXTs we decided to trim all data obtained within ∼1300 days after the peak of the outburst. This leaves 127 useful spectra of V404 Cyg (all since 1993), 94 of BW Cir, and 3 of GRO J0422+320 (from 2009).

Table 3 lists the mean FWHM and EW values for SXTs, where the quoted uncertainties represent 1 standard deviation in the distribution of individual measurements. Therefore, our errors mostly reflect time variability in line width and normalized flux. Line variability is mainly caused by aperiodic flares (Hynes et al. 2002) or long-lived disk asymmetries (e.g., hot spots), modulated with the orbital period. In the cases of N. Oph 77 and Vel 93 only one phase averaged spectrum is available and, thus, we adopt σFWHM = 0.1 FWHM to account for the average 10% variability displayed by the remaining binaries. By the same token, we adopt σEW = 0.22 EW for objects where only one spectrum is available, based on the mean standard deviation in the EWs of the remaining systems. Instrumental resolution was subtracted quadratically from every FWHM value and, therefore, the Hβ widths quoted in Table 3 are intrinsic. Table 3 also provides fundamental binary parameters, chiefly the orbital period (P), the radial velocity semi-amplitude of the companion star (K2), and the mass of the compact star (M1) and inclination (i), when available, with their associated references.

We also collected FWHMs and EWs from Hβ lines in our sample of CV spectra listed in Table 2. In the case of 14 eclipsing binaries (EM Cyg, EX Dra, HS 2325+8205, DQ Her, SDSS J100658.40+233724.4, U Gem, IP Peg, CTCV J1300–3052, HT Cas, OY Car, V2051 Oph, SDSS J130533.02+055158.3, WZ Sge, and SDSS J143317.78+101123.3) only spectra obtained ±0.05 phases away from...
the eclipse minimum were considered. As already mentioned, FWHMs and EWs values were obtained from the literature for 15 CVs. For these cases we adopt a 7% error in FWHM and 14% error in EW, derived from the mean variability measured in the other 28 CVs. These values are listed in Table 4, together with determinations of the orbital period and $K_2$ velocities.

Figure 1. Example of Gaussian fits to Hα profiles in SXTs. A selection of average spectra, representing the entire range of FWHMs, is depicted.

Figure 2. Long-term (20 years) evolution of the FWHM and EW of the Hα line in V404 Cyg. Individual points have been co-added into 50-day bins except for the first nine data points where 1-day bins were used. Errorbars reflect variability within the bin.

In Figure 3 we compare $K_2$ versus FWHM and it can be seen that these quantities are tightly correlated in SXTs, with a Pearson correlation coefficient $r = 0.99$. A linear fit yields the following relation:

$$K_2 = 0.233(13) \text{ FWHM},$$

where both quantities are given in km s$^{-1}$. A second order polynomial fit is not justified since the constant coefficient is consistent with zero at 1σ. In order to assess the error in $K_2$ estimated from the correlation, we computed the difference with the true (dynamical) $K_2$ for our 14 SXTs. The values are found to follow a Gaussian distribution with a standard deviation of 22 km s$^{-1}$. We therefore conclude that robust estimates of the $K_2$ velocity can be obtained from the width of the Hα line in SXTs. The uncertainty in the coefficient of the correlation was estimated through a Monte-Carlo simulation of $10^4$ events, assuming that the difference between the model and true $K_2$ values follow a Gaussian distribution with $\sigma = 22$ km s$^{-1}$.

The FWHM–$K_2$ correlation is expected from basic equations. Assuming that FWHM is determined by gas velocity at a characteristic disk radius $R_w$,

$$\left( \frac{\text{FWHM}}{2} \right)^2 = \frac{GM_1}{R_w} \sin^2 i,$$

where $M_0$ is the mass of the accreting star and $i$ is the binary inclination. On the other hand, the companion’s velocity is
Table 3
X-Ray Transients

| Object     | $P$ (days) | $K_2$ (km s$^{-1}$) | FWHM (km s$^{-1}$) | EW (Å) | $M_1$ ($M_\odot$) | $i$ (deg) | References |
|------------|------------|---------------------|--------------------|--------|------------------|-----------|------------|
| Black Holes |            |                     |                    |        |                  |           |            |
| V404 Cyg   | 6.47129    | 208.4 ± 0.6         | 1029 ± 94          | 19.0 ± 5.2 | 9.0$^{+0.2}_{-0.6}$ | 67$^{+1}_{-1}$ | (1), (2)   |
| BW Cir     | 2.54451    | 279.0 ± 4.7         | 1062 ± 91          | 53.4 ± 8.2 | ...              | ...       | (3)        |
| XTE J1550–564 | 1.5420333 | 363.1 ± 6.0         | 1506 ± 151         | 28.4 ± 5.8 | 11.5 ± 3.9       | 75 ± 4    | (4)        |
| N. Oph 77  | 0.5228     | 441.0 ± 6.0         | 1885 ± 189         | 68.5 ± 15.1 | 6.2 ± 1.2       | 70 ± 10   | (5)        |
| N. Mus 91  | 0.4326058  | 406.0 ± 7.0         | 1735 ± 92          | 48.7 ± 6.5 | 7.0 ± 0.6        | 54 ± 2    | (6), (7)   |
| GS 2000+25 | 0.3440915  | 519.9 ± 5.1         | 2207 ± 341         | 22.4 ± 7.2 | 5.5 ± 0.8        | 58–74     | (8), (9)   |
| A0620–00   | 0.32301405 | 437.1 ± 2.0         | 1966 ± 110         | 36.4 ± 10.8 | 6.6 ± 0.3      | 51 ± 1    | (10), (11) |
| XTE J1650–500 | 0.3205  | 435.0 ± 30.0       | 1866 ± 348         | 8.7 ± 2.3  | ...              | ...       | (12)       |
| N Vel 93   | 0.285206   | 475.4 ± 5.9         | 2082 ± 208         | 33.7 ± 7.4  | ...              | ...       | (13)       |
| XTE J1859+226 | 0.274   | 541.0 ± 70.0        | 2361 ± 109         | 129.1 ± 17.8 | ...              | ...       | (14)       |
| GRO J0422+320 | 0.2121600 | 380.6 ± 6.5         | 1716 ± 202         | 165.3 ± 18.2 | ...              | ...       | (15)       |
| XTE J1118+480 | 0.1699337 | 708.8 ± 1.4         | 2850 ± 187         | 86.7 ± 18.9 | 6.9–8.2         | 68–79     | (16), (17) |

Neutron Stars

| Cen X-4         | 0.6290522 | 144.6 ± 0.3       | 678 ± 48           | 36 ± 9  | 1.94 ±$^{+0.27}_{-0.83}$ | 32 ±$^{+5}_{-5}$ | (18), (19) |
| XTE J2123–058   | 0.24821   | 298.5 ± 6.9       | 1437 ± 272         | 18.5 ± 5.0 | 1.5 ± 0.3       | 73 ± 4    | (20), (21) |

Note.

* This column provides references for the adopted values of $P$, $K_2$, $M_1$, and $i$.

References. (1) Casares (1996), (2) Khargharia et al. (2010), (3) Casares et al. (2009a), (4) Orosz et al. (2011), (5) Harlaftis et al. (1997), (6) Orosz et al. (1996), (7) Gelino et al. (2001), (8) Harlaftis et al. (1996), (9) Ioannou et al. (2004), (10) Gonzalez Hernandez & Casares (2010), (11) Cantrell et al. (2010), (12) Orosz et al. (2004), (13) Filippenko et al. (1999), (14) Corral-Santana et al. (2011), (15) Webb et al. (2000), (16) González Hernández et al. (2012), (17) Khargharia et al. (2013), (18) Casares et al. (2007), (19) Shahbaz et al. (2014), (20) Tom sick et al. (2001), (21) Zurita et al. (2000).

The rotational broadening of the donor star $V \sin i$ (see Wade & Horne 1988), the “mean” accretion disk velocity (traced by the FWHM) scales with the donor star’s velocity. Since both are projected velocities along the line of sight, the dependence on inclination cancels out. However, unlike $V \sin i$, this new correlation is only weakly dependent on the binary mass ratio and hence results in a very tight linear regression. We also note that Equation (1) is more robust than a former empirical relation between $K_2$ and the double peak separation (Orosz et al. 1994; Orosz & Bailyn 1995) because the latter traces the tidal (outer disk) radius, which can be strongly affected by disk asymmetries, the presence of S-wave distortions driven by hot-spots, and anomalously low (sub-Keplerian) velocities (e.g., North et al. 2002).

At this point, it is instructive to compare how the CVs distribute in the FWHM–$K_2$ plane. However, prior to this it is important to assess the impact of possible selection effects. To start with, since the companion star is mostly detected above the period gap, our reference sample is, in principle, biased toward large mass ratios. The effect is further exacerbated by the fact that the CV population in the third- to four-hour period range is dominated by SW Sex and Novalike stars, systems in permanent outburst (Rodríguez-Gil et al. 2007). This explains the paucity of CVs with periods $<$0.17 days in our list. To compensate for the deficit of binaries with small $q$ values, we made an effort to incorporate short period CVs. These are, however, strongly skewed toward high inclinations because only eclipsing CVs can yield reliable $K_2$ values (through light curve modeling) when the companion star is not detected. Figure 4 presents histograms of the distribution of orbital periods, mass ratios, and inclinations in our CV sample, clearly depicting these selection effects. Mass ratios and inclination values were compiled from the references listed in Table 4 and

Given by

$$K_2 = \frac{GM_1^2}{a(M_1 + M_2)} \sin^2 i$$

with $M_2$ as the mass of the companion star. Therefore,

$$K_2 \left( \frac{\text{FWHM}}{\text{FWHM}} \right) = \frac{R_\text{W}}{4a(1 + q)}$$

where $q = M_2/M_1$ is the mass ratio and $a$ is the binary separation. If we now assume $R_\text{W} = aR_{L1}$ (with $a < 1$) and use Eggleton’s relation (Eggleton 1983) to remove $R_{L1}/a$, then

$$K_2 \left( \frac{\text{FWHM}}{\text{FWHM}} \right) = \frac{\sqrt{3}\alpha(f(q))}{2}$$

where

$$f(q) = \frac{0.49(1 + q)^{-1}}{0.6 + q^{2/3} \ln \left( 1 + q^{-1/3} \right)}.$$
Ritter & Kolb (2003). In the figure, we make a distinction between CVs above and below/within the period gap.

Figure 4 shows that the distribution of mass ratios is clearly bimodal and can be described by two Gaussians: 32 long-period CVs cluster at $q = 0.63$ with $\sigma = 0.2$ while 11 short-period CVs define a much narrower peak centered at $q = 0.12$ and with $\sigma = 0.07$. We note that, overall, this is similar to the distribution of mass ratios obtained from the entire CV data available in Ritter’s catalog (Ritter & Kolb 2003). The figure also highlights the fact that our short period CVs are strongly
biased toward high inclinations. By contrast, there seems to be no significant bias in the inclination of CVs above the gap. In view of this, we find that it is justified to distinguish hereafter between short-period CVs (i.e., below/within the gap) and long-period CVs (above the gap), with the latter not being strongly affected by selection effects.

The bottom panel in Figure 3 presents the location of the CVs in the FWHM–K$_2$ plane. The figure shows that long-period CVs display a similar regression to that found for SXTs albeit flatter, i.e., for a given K$_2$, H$_\alpha$ lines are systematically broader than in SXTs. A linear fit yields K$_2 = 0.169(16)$ FWHM, a relation that could be used to infer K$_2$ velocities for quiescent CVs above the period gap. We attribute the flatter slope of the CV correlation to their comparatively larger mass ratios, which lead to smaller R$_{L1}$ and thus smaller disk radii (in binary separation units).

If we now bring q = 0.63 (i.e., the peak in the q distribution of long-period CVs) into Equations (5) and (6) and set K$_2$/FWHM = 0.169 from the empirical fit, one obtains $\alpha = 0.43$, in excellent agreement with what was found for SXTs. This implies that the FWHM of the H$_\alpha$ line is always formed at about 42% R$_{L1}$, irrespectively of the binary mass ratio. Despite the large spread in mass ratios, the CV correlation appears to be quite narrow, a consequence of the very weak dependence of K$_2$/FWHM with q for large q values (see dotted lines in the bottom panel of Figure 3).

The group of short-period CVs, on the other hand, concentrate at large FWHM values because of their high inclinations. They are seen to depart from the trend defined by the long-period CVs, approaching the SXT correlation, a result of their small q-values. Although the short-period CVs represent a very biased sample, they are of particular interest because they define the upper limit in the FWHM distribution of the CV population.

4. THE EW–FWHM PLANE

In a given system, the FWHM of any emission line depends on the binary inclination, orbital period and the mass of the compact object. By bringing $K_2 = (2\pi a \sin i)/P(1 + q)$ into Equation (5) and using Kepler’s third Law, we find

$$\text{FWHM} \propto \frac{\sin i}{\sqrt{\alpha(1 + q)^{3/2}f(q)}} \left(\frac{M}{P}\right)^{1/3}.$$  \hspace{1cm} (7)

Here, the dependence on the mass ratio is extremely weak, with $\sqrt{(1 + q)^{3/2}f(q)}$ varying in the range 0.80–0.69 for...
Figure 5. Top: SXTs and CVs in the FWHM–EW plane. Same symbol code is used as in Figure 3, except for open triangles which now indicate CVs. Bottom panel: dashed vertical lines correspond to constant $M_i / P_i$ values (expressed in units of $M_\odot$/days) while horizontal dotted lines indicate various inclinations, in an idealized case where EWs are fortshortened by a factor of $\cos i$ due to disk continuum visibility. The green solid line limits define the maximum FWHM predicted for CVs.

$q = 0.05 - 1$. Therefore, we can safely assume

$$\text{FWHM} \approx A \left( \frac{M_i}{P} \right)^{1/3} \sin i,$$

where $A$ is a constant that can be calibrated using $P$ and FWHM values listed in Table 3, together with dynamical masses and inclinations available in the literature for nine SXTs (also listed in Table 3). These yield a mean value of $A = 876 \pm 48 \text{ km s}^{-1}$, when $M_i$ and $P$ are expressed in units of $M_\odot$ and days, respectively.

On the other hand, the EW of the $H_\alpha$ line depends on the binary geometry. For instance, Warner (1986) showed that the EW of $H_\alpha$ in CVs increases with inclination because of the reduction of continuum brightness as the disk is seen at large inclinations. Therefore, to a first-order approximation, one can assume

$$\text{EW} \approx \frac{B}{\cos i},$$

where the constant $B = 9 \pm 8 \text{ Å}$ has been calibrated using the distribution of EWs and inclinations listed in Table 3.

Figure 5 displays our sample of SXTs and CVs in the EW–FWHM plane. Here we have used open triangles to mark eclipsing CVs. BHs are a factor of $\sim 10$ more massive than white dwarfs or Ns and thus should possess, on average, wider $H_\alpha$ lines by a factor of $\sim 2.2$. Instead, we observe that only one BH (XTE J1118+480) stands out clearly in the right side of the diagram with FWHM $> 2500 \text{ km s}^{-1}$. The remaining BHs are mixed up with CVs at lower FWHM values because they either have long orbital periods (i.e., cases of V404 Cyg and BW Cir with FWHM $\sim 1000 \text{ km s}^{-1}$) or are viewed at lower inclinations. Fortunately, they cluster in the central part of the diagram between FWHM $\sim 1500–2500 \text{ km s}^{-1}$, a region populated by eclipsing CVs. Since the latter are easily detected through deep ($\sim 2$–$3 \text{ mag}$) eclipses, we conclude that non-eclipsing binaries with FWHM $\gtrsim 1500 \text{ km s}^{-1}$ are good candidates to host BHs. Incidentally, a population of (short-period) eclipsing BHs with very wide $H_\alpha$ lines would be expected in the right part of the diagram. Scaling from the eclipsing CVs, we predict them to show a factor of $\sim 2.2$ larger widths i.e., FWHM $\sim 4200 \text{ km s}^{-1}$. As a matter of fact, the transient X-ray binary Swift J1357–0933 has been proposed as an extreme inclination BH, although no dynamical solution is yet available (Corral-Santana et al. 2013). We have recently obtained 4 $H_\alpha$ spectra of Swift J1357–0933 with OSIRIS and the R300R grism on the 10.4 m Gran Telescopio Canarias (GTC) on 2013 June 29 and 30, from which we measure FWHM $= 4085 \pm 328 \text{ km s}^{-1}$ and EW $= 131.9 \pm 14.5$. These values are indeed consistent with a short period BH seen at very high inclination. The position of Swift J1357.2–0933 is indicated by an asterisk in the diagram.

Using Equations (8) and (9), one can define regions of constant $M_i / P$ and inclination in the EW–FWHM plane. These are marked in the bottom panel of Figure 5 using dashed and dotted lines respectively. We stress, however, that the quoted inclinations must be considered as merely indicative given the crude approximation involved in Equation (9). The figure suggests (with all the caveats associated with low number statistics) that, for a given FWHM, BHs tend to have lower EWs than CVs. This could be explained because, due to their shallower potential wells, CVs must be seen at higher inclinations to mimic the same projected disk velocities as BHs and, therefore, their $H_\alpha$ fluxes are less diluted by the accretion disk continuum. It is interesting to note the position of GRO J0422+320 in the upper left side of the diagram. While the mass of its BH is quite uncertain (see Casares & Jonker 2014) both the large EW and low $M_i / P$ factor suggest that it hosts a low-mass BH, in line with the results of Casares et al. (1995b) and Gelino & Harrison (2003).

Finally, we can tentatively define a forbidden region for CVs in the FWHM–EW plane by taking extreme parameters i.e., $M_i > 1.4 M_\odot$ and $P < 80 \text{ minutes}$, the period minimum spike observed in the distribution of CV periods (Gänsicke et al. 2009). This yields $M_i / P > 25.2 \text{ M}_\odot$ and thus FWHM $> 2568 \sqrt{(1 - (9/\text{EW})^2)}$, limit which is marked by a green solid line in the plot. As a test, we have examined a random sample of 236 dwarf novae selected from Sloan DR7. Sloan CVs show the same trend as seen in Figure 5, i.e., they populate the region leftward of the green line, with a large spread toward high EWs up to $\sim 350 \text{ Å}$.

5. DISCUSSION: NEW STRATEGIES TO DETECT DORMANT BHS

To make progress in our understanding of the formation and evolution of Galactic BHs it is essential to discover a large sample of secured (dynamically confirmed) BHs. This new
sample would allow us to constrain the number density, the orbital period distribution, and, ultimately, the BH mass spectrum. Only then will we be able to address fundamental questions such as the role of supernova models in shaping the distribution of BH masses, a current hot topic in the community (Özel et al. 2010; Farr et al. 2011; Belczynski et al. 2012; Kreidberg et al. 2012). Deep H\(_\alpha\) surveys of the Galactic plane, combined with spectroscopic surveys, can efficiently select samples of H\(_\alpha\) emitting objects with FWHM > 1000 km s\(^{-1}\). This width cut would allow instant removal of Galactic populations of narrow H\(_\alpha\) emitters such as planetary nebulae, Be, chromospheric stars, T Tauri, and other YSOs. Only high inclination CVs, due to the large gravitational fields of their accreting white dwarfs, are able to produce wide H\(_\alpha\) lines.

Fortunately, as we have shown, the width of the H\(_\alpha\) line in quiescent BH and NS SXTs is tightly correlated with the projected velocity of the donor star. The FWHM–\(K_2\) relation can, therefore, be exploited, together with supplementary information on orbital periods (e.g., from light curve variability), to gather “preliminary” mass functions (PMF) of compact objects from single epoch spectroscopy, i.e., PMF = \(1.3 \times 10^{-93}\) P \((\text{FWHM})^3\), where P is given in days and FWHM in km s\(^{-1}\). \(K_2\) values can be estimated from single integrations rather than expensive time resolved spectroscopy, allowing a search for dynamical BHs in much deeper fields and using a factor \(\sim 4\) lower spectral resolution than usually employed. Therefore, the novel strategy that we propose is clearly much more efficient than standard spectroscopic techniques, aiming at measuring the orbit of the donor star from the Doppler shift of weak absorption lines. This may be the only way to infer mass functions in extremely faint BH SXTs, i.e., the bulk of the Galactic population. We also note that our technique can be easily executed in crowded regions like globular clusters, where Hubble Space Telescope time-series photometry can yield orbital periods while ground-based spectroscopy is severely limited by seeing conditions.

Figure 6 demonstrates how BHs are nicely segregated from CVs and NSs using the FWHM–\(K_2\) correlation. Every BH (except GRO J0422+320) is located in the right hand part of the diagram, beyond the dotted vertical line. Therefore, targets with PMF > 2 \(M_\odot\) are strong candidates to host BHs. It should be noted that the plotted CV PMFs are, in most cases, robust upper limits to true mass functions because, by adopting Equation (1), we overestimate their real \(K_2\) values. By comparing the PMF values with the true (dynamical) mass function of BHs one can estimate the typical uncertainty introduced by the FWHM–\(K_2\) correlation. Relative errors in mass function are found to follow an approximate Gaussian distribution with \(\sigma = 0.08\). Therefore, the FWHM–\(K_2\) correlation allows us to estimate mass functions with typically \(\sim 10\%\) uncertainty. As an example, we have applied Equation (1) to Swift J1357.2–0933, where our quiescent GTC spectra yield FWHM = 4085 ± 328 km s\(^{-1}\). Extrapolating from Equation (1) we predict \(K_2 = 952 \pm 93\) km s\(^{-3}\) which, when combined with \(P = 0.117 \pm 0.013\) days, (Corral-Santana et al. 2013) leads to a record mass function PMF = 10.5 ± 3.3 \(M_\odot\). We note that this figure might even be slightly underestimated since the GTC spectra were taken only \(\sim 900\) days after the peak of the outburst (see Section 3).

In any case, the effect would be small compared to our errorbar, which is dominated by propagating the large FWHM uncertainty (driven by line variability) into the FWHM–\(K_2\) relation and the mass function equation.

A big step forward in the exploitation of the FWHM–\(K_2\) relation will likely come from the use of imaging techniques. Accurate H\(_\alpha\) widths can be measured directly through a combination of customized narrow-band filters, removing the need for any spectroscopy at all. This brings in a new observational signature that we coin here as the Photometric Mass Function (PMF, taking advantage of the same acronym used before). PMFs open a novel concept, i.e., that of weighting mass functions photometrically, and lay the ground for the efficient discovery of new hibernating BHs in large survey volumes. We are currently working on this strategy. Finally, it should be borne in mind that there is a strong selection effect against detecting high inclination BHs in X-ray selected samples. This is because flared accretion disks obscure X-rays and indeed none of the currently known dynamical BHs has an inclination >75° (Narayan & McClintock 2005). Since a PMF-based sample will be selected by H\(_\alpha\) widths and not X-ray emission, we expect that this strategy will uncover a significant number of high inclination and even eclipsing BHs. These hold the prospect to render the most accurate BH masses, yet because the relative uncertainty in the inclination dominates the mass error budget. Clearly, the newly discovered BHs will have a strategic impact in the construction of the BH mass spectrum.

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