HAWKs: a DECam Survey to unveil quiescent BHs

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Context: X-ray transients

OUTBURST: thermal-viscous instability in the accretion disc

QUIESCENCE ($L_X/L_{Edd}<10^{-5}$): companion dominates optical flux ➔ dynamical studies

$$f(M) = \frac{P_{orb} K_2^3}{2\pi G} = \frac{M_1 \sin^3 i}{(1 + q)^2}$$

$f(M) > 3 M_\odot$ ➔ dynamical BH
Distribution of Remnant Masses

XRTs give insights into binary evolution and fate of massive stars

Mass gap at \( \sim 2-5 \, M_\odot \) (Bailyn+ 98, Özel+ 10, Farr+ 11) reproduced by some recent SNe models (Belczynski+ 12, Ugliano+ 12)

But BH masses could be biased high because of systematics in inclination (Kreidberg+ 12)

Mass cap at \( \sim 15 \, M_\odot \) ? (Belczynski+ 10)

Need to increase statistics by a factor \( \sim 10 \) !!
Black-Hole discoveries

60 XRTs with BH candidates discovered in ~50 yr of X-ray astronomy, but only ~30% dynamically confirmed

18 dynamical BHs

Remaining XRTs are “lost” in quiescence because become too faint (R≥22) for dynamical studies with 10m-Telescopes

Tip of the iceberg of a large hidden population of ≈10³ quiescent BHs. New strategies required, otherwise ≈ 200 years required to increase a factor ~10 the number of dynamical BHs
Signatures of Quiescent Black Holes?

Quiescent BHs are extremely weak in X-rays (Lx~10^{31} erg/s), UV and radio (Narayan & McClintock 2008, Gallo+ 2006, Miller-Jones+ 2011)

Optical spectra dominated by K-type donor star + broad Hα emission from the accretion disc

SED of V404 Cyg  Hynes+ 09

Traditional Hα surveys might contain new BHs but outnumbered by other Hα emitting populations (CVs, T Tauri, Be...)
IPHAS/VPHAS+: Hα Surveys of Northern/Southern Galactic plane (|b|<5°) in Hα, r’ and i’ down to r’=20 (Drew+ 05,14): ~1800 sq. deg with 200 Mill objects and 10,000 Hα emitters: CVs, YSOs, Symbiotics, PNe…

GBS/CHAMPlane: Hα Surveys of Galactic Bulge and Southern Plane down to r’=22.5, cross-matched with shallow Chandra detections (Grindlay+ 05, Jonker+ 11): AGNs, coronal stars & magnetic CVs

Contamination from other (dominant) populations of Hα emitters not efficiently removed by broad-band/Hα color cuts
**FWHM-**$K_2$** correlation for quiescent XRTs**

![Graph showing correlation between $K_2$ and FWHM](image)

$$K_2 = 0.233 \ (13) \ FWHM$$

$P_{\text{orb}}$ (e.g. from light curves)

**Tight correlation:** fundamental scaling between dynamics of disc and donor

**Mass Function**

$$f(M) = \frac{P_{\text{orb}} K_2^3}{2\pi G} = \frac{M_1 \sin^3 i}{(1+q)^2}$$

**Use width of Hα line as proxy of deep gravitational fields of BH**

Analogous to reverberation mapping techniques to measure $M_{\text{BH}}$ in AGNs (Peterson+ 2004)

New concept: “Photometric” Mass Function

Discover & weigh new BHs in large FOVs

Proof-of-concept presented in Casares 2018 MNRAS 473 5195

3 custom filters centered at $H\alpha$: $r$-band, $H\alpha$-broad, $H\alpha$-narrow

SYNTHETIC SPECTRA

“Photometric Width”

$$FWHM_{ph} = C_2 \frac{EW_{ph}}{\left(\frac{EW_{ph} + W_{H\alpha b}}{W_{H\alpha n}}\right) \times \left(\frac{F_{H\alpha n}}{F_{H\alpha b}}\right) - 1}$$

with

$$EW_{ph} = C_1 \frac{W_r \times \left(\frac{F_{H\alpha b}}{F_r}\right) - W_{H\alpha b}}{1 - \left(\frac{F_{H\alpha b}}{F_r}\right)}$$

$F_r, F_{H\alpha b}, F_{H\alpha n}$: filter fluxes

$W_{H\alpha n}, W_{H\alpha b}, W_r$: filter’s EWs

$C_1, C_2$: calibration constants
New concept: “Photometric” Mass Function

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3 custom filters centered at $H\alpha$: *r-band*, *$H\alpha$-broad*, *$H\alpha$-narrow*

The 3 filters define a Photometric System tailored to measure line FWHMs (and EWs)

$FWHM_{ph}$ recovers $FWHM$ to < 5% for real data ($EW=8$-250 Å),
Cut-off width for BH selection

\( FWHM > 1500 \text{ km/s} \) would clean most Galactic populations of Ha emitters (T Tauri, chromospheric stars, Be-stars, PNe ...)

Only CVs can produce \( FWHM > 1500 \text{ km/s} \) but they are x1000 more abundant than BHs (Pretorius & Knigge12)

width of \( H\alpha_n \) determines the lower limit in \( FWHM \) selection
Filtering CVs

*FWHM > 2200 km/s* allows rejecting 99.9% CVs while still select 46% BHs

Montecarlo distribution of *FWHMs*

From empirical *FWHM-K₂* correlation and distribution of Mass functions (assuming isotropic inclinations)

**BHs:** Gaussian distributions of \( M₁ \) (mean=7.8 M\(_{\odot}\), \( \sigma=1.2 \) M\(_{\odot}\); Özel et al. 10) and \( P_{\text{orb}} \) (mean=0.29 d, \( \sigma=0.14 \) d), \( q \) (mean=0.05 d, \( \sigma=0.02 \))

**CVs:** Gaussian distribution of \( M₁ \) (mean=0.83 M\(_{\odot}\), \( \sigma=0.23 \) M\(_{\odot}\); Zorotovic et al. 11) and latest distribution of \( P_{\text{orb}} \) & \( q \) from Ritter’s (Model 1) or \( N₀ \) CVs below the gap boosted to 98% of total (Kolb 93; Howell et al. 01; Knigge 11; Model 2)

Implies a discovery rate \( \sim 2 \) CV/BH

(compared to \( \sim 200 \) CV/BH for FWHM > 1800 km/s)
Filtering CVs

\[ FWHM \propto \left( \frac{M_1}{P} \right)^{1/3} \sin i \]

Limit case for \( M_1 < 1.44 \, M_{\odot} \) and \( i < 90^\circ \) constrains \( P_{\text{orb}} \) for \( FWHM > 2200 \, \text{km/s} \)

- BHs
- Eclipsing CVs
- Non-eclipsing CVs

CVs with \( FWHM > 2200 \, \text{km/s} \) will have \( P_{\text{orb}} \leq 2.1 \, \text{h} \) and will all be eclipsing!!
**HAWKs** = **HAlpha Width Kilo deg Survey**

1. > 90% BH XRTs located in the **Galactic Plane at** |b|<10°
2. Focus on **low extinction windows** to maximize surveyed volume (e.g. W1 at l~55-75°). Southern Plane regions will be soon available from **DECAPS** (Schlafly’s talk).

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**Perseus-Sagittarius interarm region**

**IPHAS** (Sale at al. 14)

\[ A_r \leq 3 \text{ mag up to } \approx 12 \text{ kpc for } b \geq 2° \]
4-m Blanco Telescope + 3 deg² DECam

- **Single pointing**: 3 h required to reach $\text{SNR}=50$ for $r=22$ in $r$, Hab, Han (or $r=24$ at 5% photometry) goal for 10% accuracy in $\text{FWHM}_{ph}$
- Thus $\sim 20$ nights required for pilot $200$ deg² or $\sim 100$ nights for $\sim 1$ Kdeg²
- **Continuous r/Hab/Han cycles** will yield $3h$ light curves to (1) average out flickering variability and (2) detect eclipsing targets (all outlier CVs)
Hα Colour-Colour Diagram

- For an assumed population of ~5000 Galactic BHs, a **pilot 200 deg²** survey at r=22 would unveil **≈56 Hα emitters** with **FWHM>2200 km/s**

- **38 AGNs**
- **5 CVs**
- **13 BHs**

  - dynamical BHs
  - CVs from Sloan DR-7
  - X Field stars (V, III, I)

- **Outliers** can be singled out through **mid-IR WISE colours (AGNs)** and **photometric variability** in 2 h slots: **non-eclipsing** targets will be prime **BH candidates**
**Hα Colour-Colour Diagram**

- A survey of \( \sim 1 \text{ Kilo deg}^2 \) could discover \( \approx 50 \) new dynamical BHs at \( r \approx 22 \), a 3-fold improvement over the existing population (\( \sim 100 \) yrs needed at the current discovery rate of XRTs)

[Diagram showing Hα Colour-Colour relation with data points]

- Multi-object spectrographs (e.g. 4MOST, WEAVE) and **synoptic surveys** (LSST) can recover many more BHs

- The **HAWKs** catalogue will unveil many high-inclination/eclipsing BHs, so far hampered by X-ray selection effects (Narayan & McClintock 2005)

- Plus other ancillary studies:
  - Eclipsing NSs (some could be massive)
  - Several 100 short-period (eclipsing) WZ Sge stars
  - Plus countless numbers of other **Hα emitters** (more CVs, T Tauri, Symbiotics, Be-stars…)


**HAWKs Legacy Project**

**BH demographic studies**: population size/distribution, $P_{\text{orb}}$, Masses

- Field stars (V, III, I)
  - **BLACK-HAWKs**: dynamical BHs
  - *other coloured/flavoured HAWKs*
**HAWKs Legacy Project**

**BH demographic studies:** population size/distribution, $P_{\text{orb}}$, Masses

- **Field stars** (V, III, I)
- **BLACK-HAWKs:** dynamical BHs
  - **YOUNG-HAWKs:** YSO
    - T Tauri
    - Be stars
  - **SYMBIOTIC-HAWKs:**
    - S-type
    - D-type+PNe
  - **CORONAL-HAWKs:** Coronal stars
  - **CATACLYSMIC-HAWKs:** CVs
  - **ULTRACOMPACT-HAWKs:** AM CVn
  - **WHITE-HAWKs:** WDs

**SYNERGIES WITH OTHER SURVEYS:** LSST (colours & Porb), WISE (MIR colours of AGNs & Symbiotics), VISTA (NIR colours of TTauri & Symbiotics), GAIA (parallaxes of nearby targets), 4MOST, ELT (follow-up spectroscopy), eROSITA …

- LISA calib. targets