Optical View of Galactic Binary Transients

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(with emphasis on BH Transients!)

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Introduction: Transient XRBs

- **Transient/Persistent**: Phenomenological classification established by first X-ray missions

\[ \approx 10^3 \text{ Transients} \]

\[ \approx 150 \text{ Persistent (} \approx 50 \text{ optical counterparts)} \]
Disc Instability Model (DIM)

Outbursts caused by thermal-viscous instability when Teff~8000 K

Critical Mass Transfer Rate separates persistent/transient XRBs (depends on $P_{\text{orb}}$, $M_x$, irradiation)

Disc Instability Model (DIM)

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**BHs** have a larger incidence among transients than **NSs**
**X-ray transients**

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

**OUTBURST:** optical emission
dominated by X-ray irradiated disc
Quiescence: Dynamical Masses

Spectroscopy: mass function (+ mass ratio through V sini)

\[ f(M) = \frac{P_{\text{orb}} K^3}{2\pi G} = \frac{M_X \sin^3 i}{(1 + M_* / M_X)^2} \]

\[ f(M) > 3 M_\odot \quad \rightarrow \quad \text{BH} \]

\[ f(M) = 6.08 \pm 0.06 \, M_\odot \quad \text{in V404 Cyg} \]

(Casares et al. 1992; 1994)

Photometry: ellipsoidal light curves \quad \rightarrow \quad \text{binary inclination}

GRO J1655-40
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V404 Cyg

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GRO J1655-40

\[ i = 69.5 \pm 0.1^\circ \, (\text{Orosz & Bailyn 1997}) \]

\[ i = 70.2 \pm 1.9^\circ \, (\text{Greene et al. 2001}) \]

\[ i = 68.7 \pm 1.5^\circ \, (\text{Beer et al. 2002}) \]

But GRO J1655-40 is an “oddball” (F6IV companion)
Rapid aperiodic variability


Survey of quiescent XRTs at ~1-5min resolution

All quiescent SXTs show flaring activity when observed at high speed

Swift J1357-0933 (Shahbaz et al. 2013)

Most groups ignored non-stellar contamination, reported inclinations show significant scatter (see review in Casares & Jonker 2014 SSRv 183 223)
Distribution of Remnant Masses


Smooth distribution of progenitor masses drives a continuous distribution of remnants

Mass gap at ~2-5 M\(_{\odot}\) (Bailyn et al. 1998, Özel et al. 2010, Farr et al. 2011) reproduced by some recent SNe models (Belczynski et al. 2012)

But the mass gap could be biased by systematics when neglecting contaminating light in ellipsoidal fits (Kreidberg et al. 2012)

Clearly more (unbiased) masses needed to assess significance of gap
Outburst: Bowen Technique


CIII/NIII fluorescence lines allows to trace the orbit of irradiated donor (otherwise undetected)

- GX 339-4: dynamical BH > 5.3 M☉
- Aql X-1: massive NS > 1.6 M☉?
- First mass constraints in transient MSPs (SAX J1808.4-3658, XTE J1814-338)

And further measure time delays between X-rays and Bowen reprocessed light versus orbital phase (Echo-tomography)
Swift J1357-0933: VFT or very high inclination?

- Peculiar XRT with very faint peak $L_x \approx 10^{35}$ ergs/s

X-rays support a BH: Power-Law with $\Gamma \approx 1.6$ + DiskBB with $kT \approx 0.21$ keV and band-limited noise  ➔ First BH VFT (Armas-Padilla et al. 2013, 2014)

- Extremely broad Hα with $FWHM = 3300$ km/s

Current widest Hα in XTE J1118+480, with $FWHM \approx 2500$ km/s: 8 M$_\odot$ BH in 4.1 h orbit and $i=68$ deg

- Hα velocities modulated with $P_{orb} = 2.8 \pm 0.3$ h

Corral-Santana, Casares et al 2013 *Science* 339 1048
Swift J1357-0933: VFT or very high inclination?

Corral-Santana, Casares et al 2013 Science 339 1048

Remarkable optical light curves with 0.8 mag dips every ~2-8 mins

Prototype of missing population of BH XRTs with extreme inclination (Narayan & McClintock 2005)
BH X-ray Transients

55 BH XRTs discovered in 45 yrs at $\sim 1.7$ yr$^{-1}$ (since mid-80’s)

17 dynamical BHs

Most XRTs are “lost” in quiescence because they become too faint ($R>23$) for dynamical studies with 10m-Telescopes

$\sim 10^3$ hibernating BHs in the Galaxy but difficult to uncover (van den Heuvel 1992). New strategies required e.g. GBS survey (Jonker et al. 2011)
Signatures of Quiescent Black Holes?

Quiescent BHs are extremely weak in X-rays ($L_x \sim 10^{31}$ erg/s) and radio (Narayan & McClintock 2008, Gallo et al. 2006, Miller-Jones et al. 2011)

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

SED of V404 Cyg Hynes et al. 2009

Hα surveys (such as IPHAS) might unveil new BHs but outnumbered by other populations of Hα emitters (CVs, T Tauri, Be...)
FWHM-K2 correlation for quiescent SXTs


Database of 747 spectra of SXTs (12 BHs & 2 NS) and 1154 spectra of CVs (43 dwarf novae)

\[ K_2 = 0.233 (13) \text{ FWHM} \quad \text{SXTs} \]

\[ K_2 = 0.169 (16) \text{ FWHM} \quad \text{CVs} \]

- Flatter correlation for CVs

- Expected from basic equations:

\[
\frac{K_2}{\text{FWHM}} = \frac{\sqrt{1 + q}}{2}
\]

\[
f(q) = \frac{0.49 (1 + q)^{-1}}{0.6 + q^{2/3} \ln(1 + q^{-1/3})}
\]

Weak dependence on \( q \)
**f(M) from single-shot low-res Hα spectroscopy**

Extend dynamical studies ~2 mag deeper than now possible

**FWHM-K₂ correlation**

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

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

Preliminary Mass Function (PMF)

**Application to Swift J1357-0933**

Mata Sánchez et al. 2015 MNRAS 454 2199

GTC spectra in quiescence show no signs of absorption lines from donor

**FWHM (Hα) = 4152 ± 209 km/s**

**K₂ = 967 ± 49 km/s**  \[ \Rightarrow f(M)=11.0 ± 2.1 \, M_\odot \]**
Novel Technique: search for new BHs through imaging

Customized narrow-band filters optimized to select targets with very broad Hα emission lines

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

Only high inclination CVs can produce broader Hα lines but photometric periods would yield PMFs

New Concept: Photometric Mass Function (PMF)

Very efficient search of “hibernating” BHs in large FOVs
First BH with a Be-type companion

MWC 656: Be binary with 60.4 d period and γ-ray candidate

- Unusual HeII λ4686 double-peaked emission which moves in anti-phase with the Be star.

- Produced in an accretion disc around the companion of the Be.

- Double-line spectroscopic binary: eccentric orbital solution implies the companion is a BH of 4-7 $M_\odot$

Remarkable because ~80 NS/BeXBs known in the Galaxy (discovered through transient X-ray outbursts) but no BH/BeXB
At $d=2.6\pm0.6$ kpc MWC 656 is relatively close and one of the (optically) brightest BeXBs. Many other MWC656-clones may exist in the Galaxy.

14ks XMM-Newton

**Selection bias:** $L_X = 4 \times 10^{31}$ erg/s ($=7 \times 10^{-8} L_{\text{Edd}}$). Comparable to BH transients in quiescence. The accretion disc in MWC 656 is also in a quiescent state.

BeXBs have very low mass transfer rates (peak values $\approx 10^{-11} M_\odot/yr$ near periastron) which imply extremely long outburst recurrence periods.

**Dormant condition + lack of solid surface** explains why BH BeXBs are very difficult to detect through X-ray surveys.
Conclusions

• Determination of system parameters ($P_{orb}$, Masses) in transient XRBs best done in quiescence, but systematics in light curves can bias inclination and Masses

• Bowen Technique can yield $P_{orb}$ and $f(M)$ in outburst but several limitations prevent to obtain accurate masses

• $FWHM-K_2$ correlation would allow (1) extend dynamical studies ~2 mag deeper and (2) search for new “hibernating” BHs in large FOV.

• MWC 656 suggests may be a significant population of “transient” BHs fed by Be stars but with very long recurrence periods.