SPECTROSCOPIC EVIDENCES FOR A LOW-MASS BLACK HOLE IN SWIFT J1753.5-0127

Vitaly Neustroev (University of Oulu)
Collaborators

- University of Oulu:
  - Alexandra Veledina
  - Juri Poutanen
  - Sergey Tsygankov
  - Jari Kajava

- OAN SPM (Mexico):
  - Sergey Zharikov

- AAVSO:
  - George Sjoberg

University of Turku
ESA/ESAC
According to the current convention, the black holes are compact objects, whose measured masses exceed the limit of $3M_\odot$. (Belczynski et al., 2012)
An atypical X-ray transient system: the outburst was reported on 2005 May 30 and is still on-going (already 9 years!).

SWIFT J1753.5–0127 shows, in an optical light curve, relatively strong modulations with a period of 3.24 h. They were attributed to a superhump period (Zurita et al. 2008).

Observational properties evidence that the binary hosts a black hole. However, the mass of the primary was not dynamically measured.
Double-peaked $\text{H}\alpha$ and He II 4686 lines were observed immediately after the initial outburst

(Torres et al. 2005a, 2005b).
Optical spectra: no features

Cadolle Bel et al. (2007): 2005 August 11

Durant et al. (2009): 2006, 2007 and 2008.

The X-ray Universe 2014 (Dublin, Ireland)
New Observations

- Far-UV HST/COS spectroscopy:
  - October 8, 2012: 2 orbits (≈4000 sec)
    - The Far-UV G140L grating (spec. resolution ≈0.5 Å)
  - October 2, 2012 (Froning et al. 2013)
    - The Near-UV G230L grating

- OAN SPM optical spectroscopy:
  - August 2013: 54×15 min spectra (≈4000–7000 Å)

- Johnson- Cousins BVRI photometry
  - Several sets (2012-2013)
The spectrum is dominated by broad and double-peaked emission lines of C IV and He II. All absorption lines are of interstellar origin.
Optical spectrum

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Optical spectrum
Optical photometry (V and i filters)
The power spectra are dominated by a peak at **2.85 hr**, that is close to the one-day alias of Zurita et al.'s period.
Radial Velocity of the Donor star

Trailed spectrum shows sinusoidal trails of absorption and emission features.
Cross-correlation

CCFs show very strong and distinct peak
Radial Velocity of the Donor star

$K_{2,0} = 382 \pm 8 \text{ km/s}$
Emission lines are now much wider than during Torres et al.’s observations.

The lines are **VERY** wide.

Peak-to-Peak separation:

- $\text{H}\alpha$ (Torres) $\rightarrow$ 1200 km/s
- $\text{H}\alpha$ $\rightarrow$ 1650 km/s
- $\text{He II 4686}$ $\rightarrow$ 2660 km/s
- $\text{He II 1640}$ $\rightarrow$ 3200 km/s
Emission line profiles

The lines have very steep wings.

The shape of the double-peaked profile wings is controlled by the density distribution of the emitting atoms:

\[ f(r) \propto r^{-b} \]

\( b \) is usually in range of 1—2, rarely being less than 1.5.
Emission line profiles

A0620 − 00: \( b \approx 1.5 \)

XTE J1550 − 564: \( b \approx 2.0 \)

Johnston et al. 1989

Orosz et al. 2002
The X-ray Universe 2014 (Dublin, Ireland)
Emission line profiles

\( f(r) \propto r^{-b} \)

\( b \) is usually in range of 1—2, rarely being less than 1.5

In Swift J1753 \( b \approx 0.5 \)
Orbital variability of emission lines

Equivalent Widths

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Doppler Tomography

Asymmetric structure

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System Parameters

- Mass Function:

\[ f(M) = \frac{K_2^3 P_{\text{orb}}}{2\pi G} = \frac{M_1^3 \sin^3 i}{(M_1 + M_2)^2} \]

- The secondary star is likely irradiated by the X-ray source

- \( K_2 \) must be corrected!
  \( K_{2,0} / K_2 \approx 0.9 \)

- \( f_0(M) = 0.69 \pm 0.04 \, M_\odot \)

\[ f(M) \lesssim 0.95 \, M_\odot \]

One of the lowest measured mass function for a BH in a LMXB!

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Assumptions:

- The secondary star fills its Roche lobe.
  \[ M_2 = 0.1 - 0.3 \, M_\odot \]
- The double-peaked emission lines originate in an accretion disc.
- The Keplerian velocity in the disc:
  \[ V = \sqrt{\frac{GM}{R}} \]
- The outer parts of a large accretion disc are under the gravitational influence of the secondary star, which prevents the disc from growing larger than \( R_{\text{max}} \):
  \[ \frac{R_{\text{max}}}{a} = \frac{0.6}{1 + q} \]
Combine with Kepler’s third law and get:

\[(M_1 + M_2) \sin^3 i = \frac{0.074PV_{out}}{G}\]

Adopting Torres et al.’s \(V_{out} = 600 \text{ km/s}\), we obtain:

\[(M_1 + M_2) \sin^3 i = 1.2M_{\odot}\]
Constraints on the inclination

- The emission line are strongly dependent on orbital inclination:
  - Low inclination systems show spectra mainly in absorption (La Dous, 1991).
  - Intermediate-to-low inclination systems show P Cyg profiles and/or blueshifted deep absorptions.
- Strong photometric and spectroscopic orbital variability.
Constraints on the inclination

\[ i = 30^\circ \quad i = 40^\circ \quad i = 50^\circ \quad i = 60^\circ \]
Constraints on the inclination

- The emission line are strongly dependent on orbital inclination:
  - low inclination systems show spectra mainly in absorption (La Dous, 1991).
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- Strong photometric and spectroscopic orbital variability.

- **SWIFT J1753.5-0127** should be a relatively high inclination system (>40°)
**System Parameters**

**Measurements and Assumptions:**
- Orbital period: 2.85 h
- The secondary star fills its Roche lobe: \( M_2 = 0.1 \text{–} 0.3 \, M_\odot \)
- Inclination \( i > 40^\circ \)
- \( M_1 > 2.5 \, M_\odot \)

**Constrained system parameters**
- \( i=40^\circ \text{–} 45^\circ \) (51°)
- \( M_1 / M_\odot = 2.5 \text{–} 3.1 \) (4.1)
- \( q = 0.04 \) (0.03) – 0.12
- \( a / R_\odot = 1.4 \text{–} 1.53 \) (1.67)
For the observed $K_2$, upper limit for $M_1$ is $3.1M_\odot$ at a 68% confidence and $3.3M_\odot$ at 95% confidence.

For the K-correction applied, these limits are $4.0M_\odot$ and $4.3M_\odot$, respectively.
Mass distribution of compact objects

SWIFT J1753.5−0127

Belczynski et al., 2012
Mass distribution of compact objects

Özel et al., 2010

The X-ray Universe 2014 (Dublin, Ireland)
We report the re-appearance of the broad emission lines in the previously featureless optical spectrum.

We measured a possible orbital periodicity of 2.85 h, significantly shorter than the reported 3.2 h periodic signal by Zurita et al. (2008).

We estimated the system parameters of Swift J1753.5-0127. We constrain the BH mass to be below 4.3M☉.

Thus, SWIFT J1753.5–0127 is a BH binary that has one of the shortest orbital period and hosts probably one of the smallest stellar-mass BH found to date.
SWIFT J1753.5−0127

A schematic representation of the suggested geometry

THANK YOU!

The X-ray Universe 2014 (Dublin, Ireland)