Characterizing the Black Hole Candidate AT2019wey using NICER and Multi-wavelength Observations

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Galactic Low-mass Black Hole Binaries (LMBHBs)

Jet: Radio/mm/IR

Inner Accretion Disk: X-ray/Gamma-ray

Outer Accretion Disk: UV/optical

Companion: optical/IR (faint)
LMXBs: State Transition

Remillard & McClintock+2006

Energy Spectrum

Power Density Spectrum

High-soft State (HSS)

Hard Intermediate State (HIMS)
Soft Intermediate State (SIMS)

Low-hard State (LHS)
A hysteresis ("q"-shape) loop on the hardness—intensity diagram (HID)
quiescence → LHS → IMS → HSS → IMS → LHS → quiescence
LMXBs: Disk-Jet Coupling

Fender+2004
LMBHB: the known sample

Find sub-luminous LMBHBs

BH luminosity function, demographics

Study **hard-only outbursts**

- Lower peak luminosities
- Lower mass accretion rates
- Shorter orbital periods

Corral-Santana+2016

Discovered by X-ray All Sky Monitors (ASMs)

- **Swift/BAT** (15—150 keV), sensitivity @ ~16mCrab
- **MAXI** (2—10 keV), sensitivity @ ~10mCrab
- Monitoring of the Galactic Center
AT2019wey

- Discovered by SRG in March 2020, ~1 mCrab
- Palomar/Keck spectra show hydrogen lines at $z=0$

Optical first detection by the ATLAS sky survey in Dec 2019

Yao+2021a
**NICER X-ray Light Curve**

![NICER X-ray Light Curve](image)
On the HID, AT2019wey did not follow the “q-shape” track similar to MAXI J1836-194 (Lucchini+2021), perhaps common in hard-only outbursts.
The brightening was due to the appearance of a thermal component; But the power-law component was always a significant contribution.
NICER X-ray Timing Evolution

(a) (b) (c)

Time (MJD)

59070 59075 59080 59085 59090 59095 59100 59105 59110 59115 59120

NICER count rate

MAXI (counts s⁻¹)

Chandra

Frequency × (RMS/Mean)² Hz⁻¹

0.1 1 10 100

Frequency (Hz)

0.1 1 10 100

Frequency (Hz)

0.1 1 10 100

Frequency (Hz)

Yao+2021a
**NICER X-ray Timing Evolution**

On the absolute rms-intensity diagram (RID), AT2019wey follows the hard-line (HL): fractional rms ~ 30%; and left the HL around 2020 Aug 21.
Broad-band X-ray Spectra

- LHS: power-law $\Gamma = 1.7$
- Rising LHS: relativistic reflection

Inclination $i < 30^\circ$

Direct power-law

“reflection” spectrum

Yao+2021a
Broad-band X-ray Spectra

- LHS: power-law $\Gamma = 1.7$
- Rising LHS: relativistic reflection
- HIMS: reflection fraction grows

Swift/XRT
SRG/ART-XC
INTEGRAL/IBIS

Mereminskiy+2022

$E_{\text{cut}} > 700$ keV
NICER's great spectral-timing power shows that AT2019wey's X-ray State Transition Follows Low-hard state $\rightarrow$ hard-intermediate state.

VLA radio spectral energy distribution

X-ray and Radio Brightened Together Disk-Jet Coupling

2020-05-27 2020-08-21 2020-08-02 2020-08-28 2020-08-14 2021-02-17
VLBI Observations: Detection of a Resolved Jet

The 5th XRB with resolved jet detected

Sep 2020
VLBA 4.8 GHz

Scatter broadening from Galactic ISM

Oct—Dec 2020
EVN, VLBA multi-frequency

Yadlapalli, Ravi, Yao +2021

Cao+2022

\[ D > 6 \text{ kpc} \]
Why is AT2019wey a Black Hole Candidate?

1. Position on the $L_R-L_X$ diagram: closer to BHs (radio luminosity is high)

2. Position on the $\Gamma-L_X$ diagram: closer to BHs (power-law index is hard)

3. Position on the $L_{\text{opt}}-L_X$ diagram: closer to BHs (optical luminosity is high)

4. Relatively high power-law cutoff energy ($E_{\text{cut}}>700$ keV)

* No pulsation detected in the first 400ks of NICER observations (by Mason Ng).
Comparison with other BH outbursts

- Long duration of the initial LHS; Two plateau phases
Comparison with other BH outbursts

- Long duration of the initial LHS; Two plateau phases
- Analogous to the “Z Cam” type of dwarf novae

Figure 3.21 Light curves of Z Cam showing standstills. From AAVSO observations.

See discussion of BH binary “standstill” outbursts in Esin+2000, Shaw+2019
Empirical relation between BH optical outburst amplitude and orbital period:
\[ \Delta V = 14.36 - 7.63 \log(P_{\text{orb}}/\text{hr}) \]
Shahbaz+1998 \( \Delta r > 5.2 \rightarrow P_{\text{orb}} \lesssim 16 \text{ hr} \)

X-ray flux increase \( \times 25 \)
Optical flux increase \( \times 1.3 \)
Origin of UV/Optical Emission in LHS & HIMS

\[ L_{\text{opt}} = A L_{\text{X}}^{\beta} \]

- AT2019wey: $\beta \sim 0.1$
- Most other LMBHBs: $\beta \sim 0.6$ (irradiation/jet)  

**Intrinsic thermal emission from accretion disk with $R_{\text{in}} > 100 R_s$.**

**X-ray reprocessing at the outer accretion disk.**

Russell+2006

Yao+2021b
Optical/IR Spectra

- Only H I and He I; No obvious He II in emission
- Hα: single-peaked emission core
- The emission core is stronger during HIMS
Summary

- AT2019wey is a new X-ray transient discovered by SRG in March 2020
- **NICER spectral-timing analysis** suggests that the X-ray outburst transitioned from the canonical LMXB LHS to the HIMS
- $M_2 < 1\, M_\odot$, $P_{\text{orb}} \lesssim 16\, \text{hr}$; inclination $i < 30^\circ$ (from NICER+NuSTAR)
- Good black hole candidate: high radio/optical luminosity; hard $\Gamma$ in LHS; hard X-ray power-law cutoff not observed
- Very long durations (months—years) in both the LHS and the HIMS → analogous to “Z Cam” dwarf novae, **stable mass transfer**
- Origin of UV/optical emission: intrinsic disk emission during LHS; irradiation at outer disk during HIMS

References:

  Mereminskiy et al. 2022, A&A, 661, 32