Tick Tock: A Spectroscopic Investigation into an Imminently Merging Supermassive Black Hole Binary Candidate

Abstract: We request 8.5 hours of optical and 1.5 hours of near-infrared spectroscopic monitoring during semester 2023A in order to investigate a proposed supermassive black hole binary (SMBHB) merger and determine whether it is truly a binary merger or some other form of AGN variability (e.g., a changing look quasar or disc precession). SDSS J1430+2303 was recently identified as being an imminent SMBHB merger (within the next 3 years), and the closest candidate (< 1Gpc away). SMBHB mergers represent the most massive mergers in the universe, producing the "loudest siren" of gravitational waves detectable by space-based detectors. We will monitor several broad line region spectral lines to search for periodic line shifts due to SMBH binary orbit motions and/or emission profile variations that will rule this source in (or out) as an SMBHB merger. Either outcome would be compelling scientifically and of interest to the broader astronomical community.

Scientific Justification *Limited to 1 page of text plus 2 pages for figures and references.*

Supermassive black hole binary (SMBHB) mergers represent the most massive mergers in the universe, producing the "loudest siren" of gravitational waves. SDSS J143016.05+230344.4 (hereafter SDSS J1430+2303, the so-called "tick tock" SMBHB) was recently identified by [1] as being an imminent SMBHB merger (within the next 3 years), and the closest candidate ($<$ 1Gpc away). We request optical and near-infrared (NIR) spectroscopic monitoring in semester 2023A to investigate whether this is truly an SMBHB merger, or some other form of AGN variability. This study will also allow us to test whether spectral variability-monitoring can be used to identify SMBHB mergers whose gravitational wave signals may be detectable by space-based detectors such as the Pulsar Timing Array and LISA.

The primary science goal of this proposal is to perform optical and NIR spectroscopic monitoring of SDSS J1430+2303's broad-line region (BLR) for two months during 2023A to search for evidence of pre-merger periodic accelerations and/or a post-merger recoil kick. We request 900s (3x300s) observations of the broad Hα and Hβ lines every 5 days using GMOS-North from April 1 - May 31 2023, for a total of **8.5 hours**. Additionally, we will take a **1.5 hour** snapshot of the broad Pa-α line using GNIRS concurrent with one optical observation. For the optical data, we will compare with observations taken in program GN-2022A-DD-101 (Feb-April 2022), as well as earlier spectra in [1] (see Figure 2), establishing a long baseline of study for this source.

If SDSS J1430+2303 is a SMBHB, predictions indicate it may merge anytime between mid-2022 and 2025, **with the highest likelihood of merging in 2023** (see optical-only probability distribution function (PDF) in Figure 3, taken from [1]). Recent X-ray [2, 3], optical [4], and radio [5] observations have found variability that does not indicate a merger occurring in 2022, though the SMBHB merger scenario has not been ruled out. Our 2023A observations will probe the following scenarios:

- **Scenario A:** SDSS J1430+2303 is a SMBH binary and merges during the two month window.
- **Scenarios B:** SDSS J1430+2303 is a SMBH binary, but does not yet merge.
- **Scenario C:** Variability in SDSS J1430+2303 is due to other distinguishable physical mechanisms (i.e. changing look quasar, precession).

Scenarios A/B: We are now within the time range when SDSS J1430+2303 is predicted to merge, but no merger has yet been observed. If SDSS J1430+2303 is an imminent SMBHB merger, our 2023A monitoring will enable us to view the merger inspiral in real time. Our observations target the Hα, Hβ, and Pa-α lines, which are emitted by different parts of the broad line region (BLR) in an AGN. The BLR is photoionized and gravitationally bound to the SMBH [6,7], so periodic velocity shifts of the broad lines can be attributed to the orbital motion of the two BHs (see Figure 1 for an illustration). In **Scenario A**, the source merges during our 2023A window, and we will compare our post-merger observations with earlier observations (Figure 2 and Gemini program GN-2022A-DD-101) to determine whether there is a new broad line velocity shift due to a post-merger recoil kick. In **Scenario B**, the source shows periodic shifts in the BLR lines without merging, and we will re-propose for observations to continue monitoring.

Scenario C: Though SDSS J1430+2303 continues to show optical/x-ray variability, this could be attributed to another physical mechanism. One viable option is a changing-look quasar, which show broad line shifts and emission profile changes on short timescales [7, 8]. Disc precession around a single BH was also a proposed option by [4]. The requested BLR spectroscopic monitoring will distinguish between the SMBHB theory and these other scenarios by tracking any line shifts and emission-line profile variability.

SDSS J1430+2303 has recently been observed by VERITAS (private comm.), NICER/ NuSTAR [2,3], Chandra/Swift [3], the REM Telescope [4], VLBI [5], Hubble [10], and others, but there are no known optical spectral monitoring programs tracking periodic BLR shifts. Additionally, the Pa-α line (corresponding to a different part of the BLR) has not been investigated for a Doppler shift. Thus, this proposal represents a modest investment of Gemini time **(8.5 + 1.5 = 10 hours)** that will result in a significant scientific payoff, with a unique optical/NIR view of what could be the closest SMBHB coalescence.

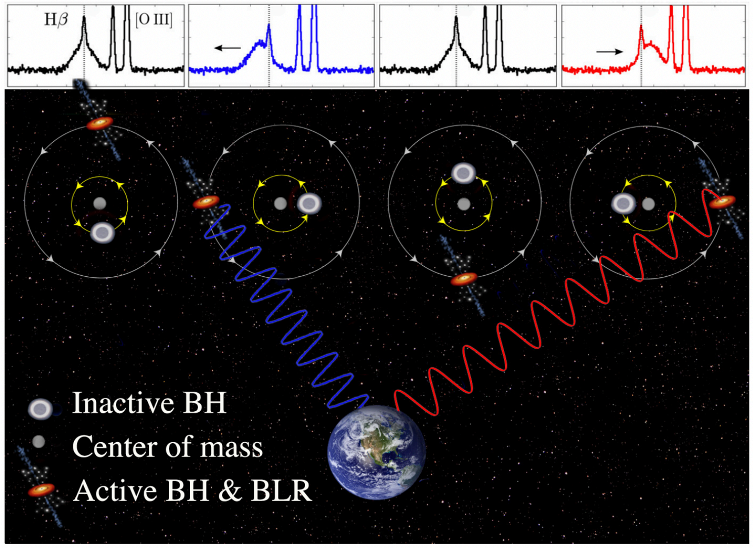

Figure 1: Illustration of a SMBH binary demonstrating velocity shifts in the BLR Hβ line (black, blue, and red spectral panels) as two black holes orbit a shared center of mass. In this illustration, only one black hole (orange) is assumed to have a BLR, but for SDSS J1430+2303 it's possible each black hole has its own BLR. Figure from [7].

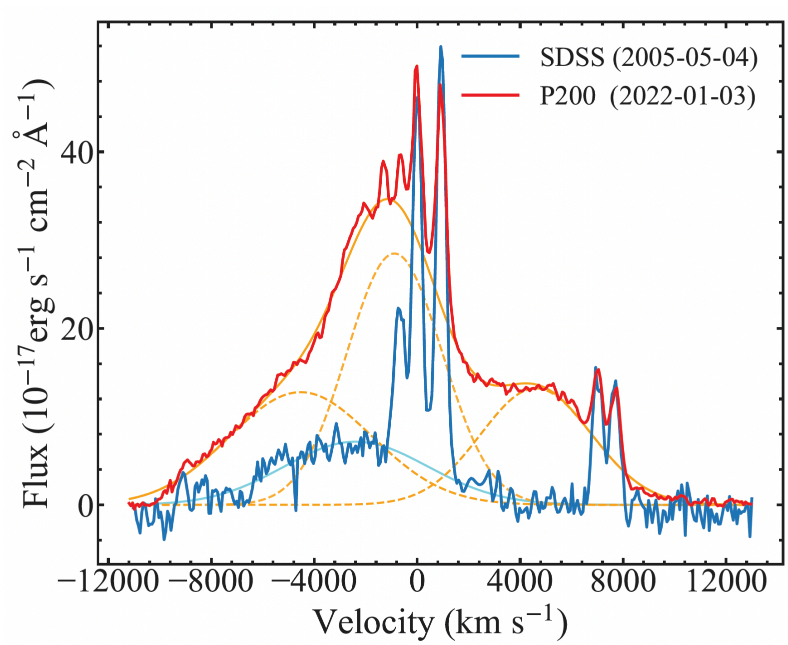

Figure 2: The complex broad Hα line of SDSS J1430+2303 in 2005 (SDSS) and January 2022 (Palomar)[1]. The SDSS spectrum has a blue-shifted velocity of $\sim$ 2400 km s^{-1}, while the Palomar observation has a more complex structure fit with three Gaussian components including a red-shifted component (4600 km s^{-1}) and a blue-shifted component (4000 km s^{-1}). Figure from [1].

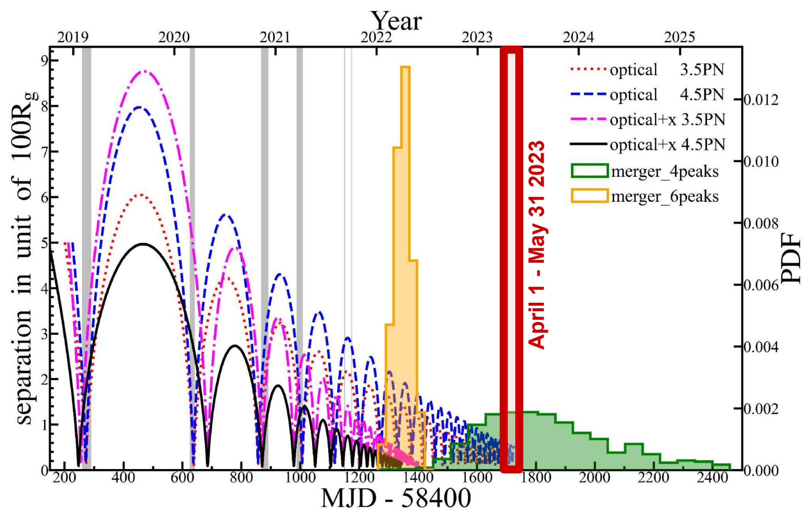

Figure 3: Several different potential binary separation evolution models up until 2025, predicted from models using either optical data (red/blue dotted/dashed lines) or optical plus X-ray data (pink and black lines). A histogram shows the probability distribution function (PDF) of the merger time using either the optical data (green) or the optical plus X-ray data (orange). If one assumes that the optical and X-ray are produced by the same physical origin, the combined optical+X-ray analysis predicts an earlier merger(mid-2022), while the optical alone suggests a merger on a somewhat later timescale, with the highest chance to occur in 2023 (green histogram peak). The proposed observing time-span (highlighted in red), falls within the highest likelihood window predicted by the optical data. Figure from [1].

Experimental Design *Limited to 1 page of text*

We request medium resolution GMOS-North spectroscopic monitoring and one GNIRS spectrum to credibly rule-in (or rule-out) the closest SMBH binary merger candidate. We will do this by measuring the BLR-emitted Hα and Hβ lines to search for pre-merger periodic line shifts due to orbital motions of the SMBHB, and/or measuring a post-merger recoil kick. We will also investigate whether the NIR spectrum Pa-α line displays a similar Doppler shift to the optical lines. The NIR emission originates from a different physical location within the BLR, and so comparing the shape of the NIR with optical lines can tell us about the spatial extent of the BLR.

A similar analysis of SDSS J1430+2303's BLR Hα line (see Figure 2) was performed by [1] using Palomar Observatory, and they claim the emission profile is fit by at least two distinct $\sim$ 4000 km s^{-1} velocity-shifted components, in addition to a 2400 km s^{-1} velocity-shifted component detected by SDSS in 2005. No periodicity in the line shifts has been identified yet. Likewise, [9] observed the BLR for one night in April 2022 using the BTA telescope, but they found inconclusive evidence for SMBHB broad line velocity shifts.

To investigate whether line profile variations are due to simple AGN variability (e.g., changing look quasar or precession), or the periodic orbital motions of an inspiralling SMBHB, we need dedicated spectral monitoring of the BLR. This monitoring will not only probe periodic BLR velocity shifts, but also reveal any periodic variability in the overall emission line profile in the specified wavelength range. Broad line shifts and emission profile variations are what will enable us to distinguish between a merging SMBHB (periodic BLR shifts but little emission line profile variation [1, 6]), a changing look quasar (BLR shifts and emission line profile variation [6, 7]), and disc precession (emission line profile variation, but no periodic BLR shifts [4]).

The optical monitoring cadence request is driven by Figure 3, the previous observing program GN-2022A-DD-101, and other telescope observations of SDSS J1430+2303's variability. The prediction from [1] as well as observations by [2,3] suggests that the binary orbital period is $\sim$ 20-30 days, however the dataset that we wish to compare the monitoring observations to is spaced $\sim$ 10 days apart. The most recent optical monitoring by [4] failed to detect periodic variability, though they found the source dimming slightly over $\sim$ 20 days. They suggest this may be due to the period decreasing to the point where their cadence/uncertainties can no longer distinguish it. In case the period has decreased, **we opt for an optical monitoring cadence of $\sim$ 5 days. We would like the NIR spectrum to be roughly concurrent with one of our 13 optical observations** for ease of comparison, but beyond that our only restriction on the execution timing is whether the observing conditions quality is sufficient (see Technical Description below). Given the many challenges to scheduling observing time, and the uncertainty in SDSS J1430+2303's period, we are flexible with the scheduling of our program and can tolerate some modifications in the optical monitoring cadence.

Technical Description *Limited to 1 page of text*

For the optical spectroscopic monitoring of SDSS J1430+2303 (RA 217.566892 deg, DEC +23.062342 deg, z $\sim$ 0.081), we request the GMOS-North instrument. Our setup is designed to match that of GN-2022A-DD-101, as we wish to achieve a similar SNR for comparison. We therefore request the following setup: the 1.0" longslit focal plane unit and the B600 grating using the Hamamatsu array, with the 615nm central wavelength. This will allow us to observe the redshifted and Doppler shifted broad Hα and Hβ emission lines while avoiding chip gaps, and reaches a spectral resolution $\gtrsim$ 1000, which is more than sufficient for measuring lines with a velocity shift $\sim 2000 - 4000$ km/s. SDSS J1430+2303 is technically an extended (0.4') galaxy target, but the central SMBH(s) BLR emission is effectively a point source, so the 1" slit is sufficient (see justification in [10]). Based on the ETC, we can achieve good SNR > 20 with 15 minutes (3x300s exposures) on target ($\sim$ 35.5 minutes including overheads). With observations every 5 days for 13 nights from April 1 - May 31 to monitor variability, this leads to a **a total optical time request (including 10% initial calibration overheads) of $\sim$ 8.5 hours**. Given that the source is bright and fluctuates between g=17.0 and g=17.5 mag, we request minimum observing conditions of: 80% sky background (grey), 70% cloud cover, 85% image quality, 1.5 airmass, and no water vapor constraint. This gives an overal execution likelihood of 50%. The source is observable from Gemini-North during the entire observing window. We will compare the resultant observations with earlier spectra presented in [1] (see also Figure 2), as well as the spectra taken through program GN-2022A-DD-101.

For the NIR spectrum, we request the GNIRS instrument with the following setup: 0.15"/pixel (short blue) camera in long-slit mode with the 1" focal plane mask and the 111 l/mm grating, with the 2000 nm (2 μm; K band) central wavelength. This reaches a medium spectral resolution $\gtrsim$ 1000. We choose the medium background read mode and shallow well depth, both recommended for the 1-2.5 μm band. Based on the ETC, we can achieve good SNR $\gtrsim$ 20 (including in the telluric absorption bands overlapping Pa-α) with 1 hour (12x300s) exposures on target ($\sim$ 1.4 hours including overheads). **This leads to a total NIR time request (including 10% initial calibration overheads) of $\sim$ 1.5 hours**. Telluric absorption is a much bigger problem in the NIR, so we request: 70% image quality, 70% cloud cover, 50% water vapor, 80% sky background (preferably darker), and 1.5 airmass. This gives an overll execution likelihood of 20%. Because we are only requesting one NIR spectrum to be taken roughly concurrently with any of our thirteen optical observations, we think our NIR request is flexible enough to be feasible with these weather constraints.

References

[1] Jiang et al., 2022, arXiv:2201.11633.

[2] Pasham et al., 2022, ATel #15225.

[3] Dou et al., 2022, A&A, 665, 3.

[4] Dotti et al., 2022, arXiv:2205.06275.

[5] An et al., 2022, A&A, 663, 139.

[6] Ilić et al., 2017, Frontiers in Astronomy and Space Sciences, 4, 12.

[7] Guo et al., 2018, MNRAS, 482, 3.

[8] Ruan et al., 2016, ApJ, 826, 188.

[9] Moiseev et al., 2022, ATel #15319.

[10] Runnoe et al, HST Proposal. Cycle 30, ID. #17208.