SAX J1808.4-3658's 2025 Outburst in the Multi-wavelength Regime

The many tones of Accretion

Dr. Kelebogile Gasealahwe | UCT - SARAO Postdoctoral Research Fellow

Collaborators: XKAT, Prof. Russell and LCO team

Scientific objective

XKAT, the successor of the ThunderKAT Large Survey Project largely monitors X-ray binaries. This study forms part of the investigation into the jet production of the neutron star X-ray binaries. Moreover, developing the underpopulated representation of neutron star X-ray binaries on the radio:X-ray correlation plane. This study, along with the complete survey further advances the comparison to the black hole X-ray binaries within the multi-wavelength regime.

Introduction and the fundamentals of SAX J1808.4-3658

Neutron Star (NS) X-ray binaries (XRBs) are binary systems comprising a NS that accretes matter from a companion star. A subgroup of these are systems with low-mass ($M_{companion} < 1\ M_\odot$) companions, and are thought to be considerably older than systems with a higher mass ($M_{companion} \gtrsim 8\ M_\odot$; Joss et al. 1978).

SAX J1808.4–3658 (SAX J1808 hereafter), is an X-ray binary with an X-ray pulsation at 401 Hz. SAX J1808 was discovered in 1998 by the Rossi X-ray Timing Explorer (RXTE) (Levine et al. 1996), and was the first confirmed AMXP (Wijnands & van der Klis 1998). SAX J1808 displays Type I thermonuclear X-ray bursts based on which a distance of 3.5 kpc was estimated (in 't Zand et al. 1998; Galloway & Cumming 2006). An orbital period of ≈ 2 hr (Chakrabarty & Morgan 1998) is known for the source. SAX J1808 is reported to go into semi-regular outbursts with recurrence times between 2 and 4 years. Previous outbursts from SAX J1808 were recorded in 1999, 2002, 2005, 2015 (Tudor et al. 2017), 2019 (Goodwin et al. 2020; Baglio et al. 2020; Bult et al. 2020; Ambrosino et al. 2021) and 2022 (Illiano et al. 2023).

The radio | X Ray correlation

In BH systems in the hard X-ray state (or: at relatively low luminosities) accretion is believed to be inefficient, as a large fraction of the gravitational potential energy is not radiated, but lost across the BH event horizon (Fender & Belloni 2012). In contrast, in NS systems accretion may be efficient as all the potential energy of the accreting matter is released at the NS surface. This may result in a steeper correlation (see e.g. discussion in Coriat et al. 2011). Multiple studies of NS systems, however, suggest that the slope of the correlation for some NS-XRBs is inconsistent with this assumption (Migliari & Fender 2006; Tudose et al. 2009; Gallo et al. 2018; Deller et al. 2015). The correlation slope of some NSs being similar to that of BHs is surprising because the physical properties are different between the compact objects. In order to develop a better understanding of the radio:X-ray correlation for NS-XRBs, a quantitative analysis of luminosity strength is required of these systems

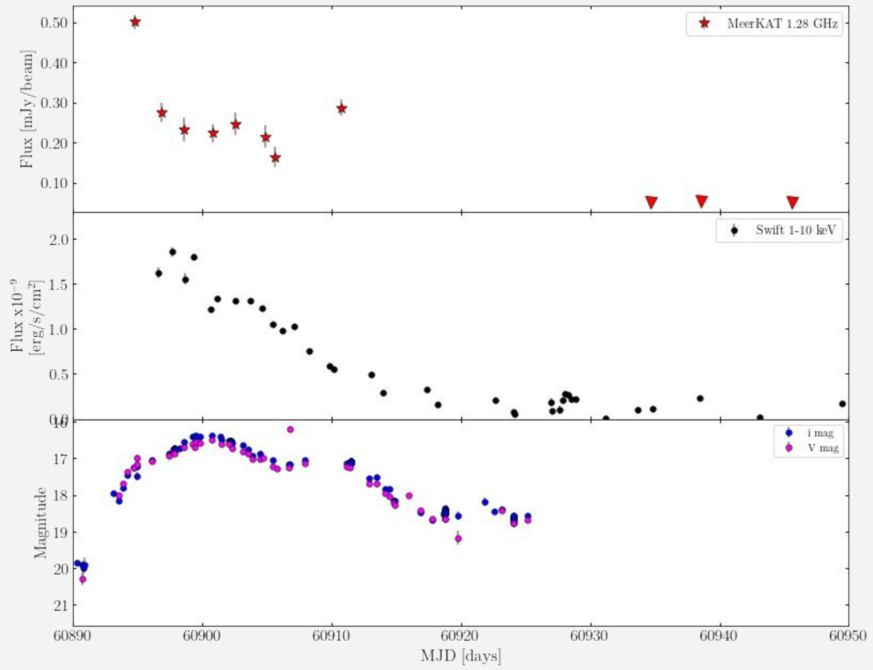

Figure 1: The multi-wavelength lightcurves of the 2025 outburst as observed from the MeerKAT radio telescope (see top panel), the Swift XRT telescope (middle panel) and the Las Cumbres Observatory optical telescope (bottom panel). The complete main outburst and subsequent reflaring events are seen in the lightcurves.

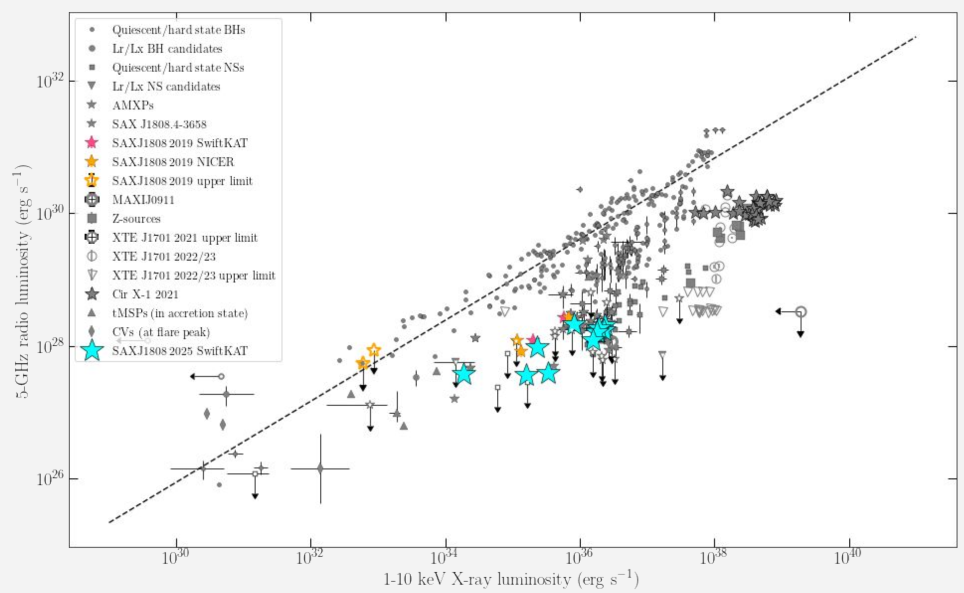

Figure 2: The radio X-ray correlation plane is described where the x-axis is the X-ray luminosity within the 1 - 10 keV band and the y-axis is the radio luminosity scaled to 5 GHz. The quasi-simultaneous radio X-ray matches are plot for previously observed X-ray binaries in grey. The 2019 outburst matches are in pink and orange and the 2025 outburst is in cyan.

Results

The multi-wavelength lightcurve described in Fig. 1 shows the radio band with red markers in the top panel, the X-ray with black markers in the middle, and the optical i and v band (blue and magenta respectively) in the bottom panel. The first report from the onset of the outburst was in the optical band, the lightcurve from that LCO data indicates that it started to brighten from MJD 60890. The X-rays were first reported from MJD 60893 (Wang et al. 2025) taken by the Einstein probe. Swift XRT started to observe the source soon after, the results from those observations are shown in the middle panel of Fig. 1.

The Swift lightcurve indicates that the start of the peak is seen from MJD 60896.64. The peak of the optical lightcurve coincides with the lowest point of the radio and X-ray main outburst decay, preceding the first rebrightening at MJD 60902.61. The radio lightcurve has a second rebrightening seen at MJD 60910.73, while the X-rays shows a short-lived rise just before then. Similarly, the optical lightcurve shows a brightening around this period and a subsequent event later on at MJD 60920. On the other hand, the X-rays appear to exhibit more short rebrightening events as the source tappered off to quiescence. The source becomes radio quiet before the full outburst is complete indicating three 3σ upper limits at MJD 60934.63, 60938.57 and 60945.55.

Discussion

The 2025 outburst of SAX J1808 provides one of the largest data sets of neutron star systems in the hard spectral state on the radio X-ray correlation plane. The 2019 outburst was analysed using the MeerKAT-Nicer and MeerKAT-Swift matches , measuring slopes of $\beta \sim 0.67 \pm 0.33$ and $\beta \sim 0.77 \pm 0.13$ respectively. The preliminary slope that is measured for the 2015 outburst is $\beta \sim 0.23$, a flatter slope. The broad range of scatter within the X-ray luminosity to the radio luminosities may account for the slope. The results may be improved by monitoring higher cadence levels for the complete outburst for both radio and X-ray bands. We therefore propose that that the 2025 slope likely shows a disparity to the 2019 slopes due to to the cadence.
Furthermore, more studies are required to investigate how this compares to black hole systems.

References

See Gasealahwe K. V. S., et al., 2023, MNRAS, 521, 2806 and references therein for complete reference list and detailed discussion. Furthermore, the 2025 results are being prepared in Gasealahwe et al in prep.