Roman CCS White Paper

X-ray binaries, cataclysmic variables and transients in the Galactic bulge

Roman Core Community Survey: Galactic Bulge Time Domain Survey

Scientific categories:
Stellar physics and stellar types
Stellar populations and the interstellar medium

Additional Keywords: Neutron stars, Stellar-mass black holes, X-ray binaries, Astrometry

Submitting Author:
Arash Bahramian
Curtin Institute of Radio Astronomy
arash.bahramian@curtin.edu.au

Co-authors: Nathalie Degenaar (Amsterdam), Craig O. Heinke (Alberta), Casey Lam (UC Berkeley), Thomas J. Maccarone (TexasTech), Sean K. Terry (UC Berkeley)

Abstract

The Galactic bulge harbors a large population of energetic systems, such as cataclysmic variables (CVs) and X-ray binaries (XRBs). The planned Galactic Bulge Time Domain Survey (GBTDS) by Roman observatory can enable a first of its kind multi-wavelength exploration of energetic transients and accreting binaries in the Galactic bulge and reveal hidden populations of compact stellar remnants in our Galaxy. Here we advocate for modification of the currently planned field to target the inner parts of the Galactic bulge and include potential coverage of the Galactic center (GC). Such a modification will leverage overlap with heavily surveyed areas of the Galactic bulge by multi-wavelength time domain surveys (particularly in the X-rays) to significantly enhance science outcomes in domains such as accretion physics around compact objects, population of compact remnants (in binaries), and rapid multi-wavelength exploration of energetic transients, without any significant negative impact on the Roman mission-requirements for the GBTDS.

1 Background and Motivation

All-sky X-ray monitors such as *MAXI* and dedicated X-ray surveys of this region by X-ray observatories such as *Chandra* and *Swift* (among others) have revealed a large population of persistent and transient accreting compact objects in the Galactic bulge (e.g., Kuulkers et al., 2007; Jonker et al., 2011, 2014; Grebenev & Mereminskiy, 2015; Wevers et al., 2016, 2017; Shaw et al., 2020; Bahramian et al., 2021) with further significant increase towards the Galactic center (e.g., Wang et al., 2002; Muno et al., 2005, 2006; Degenaar et al., 2015). For almost all of these systems, the elevated levels of interstellar extinction towards the heart of our Galaxy makes optical study of these systems unfeasible. Additionally, high levels of crowding limits the capability of large-scale follow-up by ground-based observatories. It is in this landscape that a wide-field survey of the Galactic bulge such as GBTDS with Roman provides the first ever deep and long-term coverage of these systems.

Coverage with GBTDS (particularly in the W146 filter) enables a wide array of deep novel studies in the domain of accreting stellar-mass black holes (BHs), neutron stars (NSs) and white dwarfs (WDs), ranging from exploration of accretion in exotic and poorly understood regimes to the discovery of the hidden population of compact remnants in the Galactic bulge.

A vital component of all of these studies is existing multi-wavelength coverage of these systems. Thus, in this white paper we advocate for an adjustment of the GBTDS planned fields to maximize overlap with existing X-ray surveys of the Galactic bulge and Galactic center. Such a modification can increase *Chandra* X-ray sources covered by GBTDS from 1700 to 7800, while having minimal effects on the mission science requirements of the survey.

2 Science cases

2.1 A detailed multi-wavelength view of accretion phenomenology in X-ray binaries

Understanding accretion in the extreme regime In contrast with typical XRBs, which show peak X-ray luminosity of $L_X \sim 10^{37}$ erg s^{-1}, a subset of these systems which are known as very faint X-ray binaries (VFXBs) show peak accretion luminosities of $L_X \lesssim 10^{36}$ erg s^{-1}(Wijnands et al., 2006). This underluminous accretion behaviour is thought to be associated with parts of the evolution of X-ray binaries that are currently poorly explored. For example, low-mass X-ray binaries that accrete through Roche-lobe overflow for most of their life are speculated to go through a phase of wind accretion (Pfahl et al., 2002; Maccarone & Patruno, 2013). At the other end of accreting binary evolution, VFXBs may present the slow final evolution of systems with $\sim$0.01 $M_\odot$ degenerate companions.

VFXBs are difficult to study across the electromagnetic spectrum, as they fall below the typical sensitivity of most X-ray all-sky monitors. Dedicated X-ray surveys of the Galactic bulge over the past two decades have led to discovery of dozens of VFXBs in the region, and have revealed that VFXBs may outnumber "canonical" XRBs (Muno et al., 2005; Degenaar & Wijnands, 2009; Degenaar et al., 2012). The faintness of their optical/near-infrared counterpart also makes characterization of the companion and mass-transfer in the system extremely challenging.

GBTDS will enable identification of near-infrared counterpart to dozens of known VFXBs, opening the door to a deep systematic study and characterization of the companion star in these systems. Furthermore, the long-term time-domain coverage of these system enables characterization of mass-transfer and its variability. History of X-ray activity and detection is a vital part of classification of VFXBs. Thus maximizing overlap of GBTDS with existing X-ray coverage of the area significantly enhances this area of exploration with Roman.

Constraints on accretion characteristics in transient and persistent accreting systems Traditionally, outbursts from accreting BHs and NSs have been initially detected in the X-rays, and then followed by targeted multi-wavelength observations in the optical/near-infrared bands. This has hampered our capability to form a complete picture of how the accretion disk evolves through an outburst, particularly at the start of an outburst, which holds key information about how outbursts and episodes of enhanced accretion start in XRBs and how the effects propagate through the accretion disk. A fundamental observational component to understand the start of the outburst is the lag between enhancement in the optical/near-infrared emission and the X-ray emission, which enables us to directly constrain the viscosity of the accretion disk. Such a multi-wavelength coverage in XRBs have only been achieved for a handful of bright nearby systems (e.g., Tucker et al., 2018; Goodwin et al., 2020).

The planned GBTDS will enable a systematic coverage of thousands of dormant XRBs. In the event of an outburst, it will provide a deep well sampled coverage of the outburst rise and evolution in the near-infrared, synchronous with X-ray coverage provided by X-ray all-sky monitors (such as *MAXI*) or ongoing surveys of the area (e.g., with *INTEGRAL* or *Swift*/XRT). This will enable a unique deep coverage of XRB outburst evolution and careful characterization of accretion and viscosity.

In addition to characterization of accretion in the initial episodes, the GBTDS will also provide unique long term coverage of near-infrared variability of persistent accreting systems in the Galactic bulge for the first time. Simultaneous long-term X-ray and near-infrared coverage of these systems will, for the first time, allow deep multi-wavelength exploration of accretion state transition on a large scale.

2.2 Discovery of hidden population of black holes and neutron stars

Discovery of compact objects in ellipsoidal binaries Over the past few years large optical surveys such as ASAS-SN, OGLE, and Gaia have opened the path to systematic identification of ellipsoidal variables, particularly ones harboring candidate compact objects (e.g., Jayasinghe et al., 2018; Thompson et al., 2020; Gomel et al., 2021, 2022). These discoveries have boosted the number of identified BHs and candidates in our Galaxy significantly and have enabled a more comprehensive exploration of BH population in our Galaxy and fundamental questions regarding their formation and growth.

However, these surveys have been limited to the optical bands which has hampered their capability to identify ellipsoidal variables (and subsequently ones harboring BHs and NSs) in the Galactic bulge and center, where a high concentration of compact objects (in various binary configurations) is both expected and observed (Liu & Li, 2006; Ruiter et al., 2006; Grimm et al., 2002; Zhu et al., 2018; Arnason et al., 2021).

Thus, Roman's GBTDS will be the first deep and wide survey to enable ground-breaking exploration of ellipsoidal variables and compact objects in the Galactic bulge. This is particularly thanks to the planned long-term time-domain coverage (4.5 yr between the first and last bulge "seasons", Penny et al., 2019) and the near-infrared filter (F146) aspects of the survey.

Identification of post-supernovae binaries from high proper-motion objects in the bulge The formation of BHs and NSs via supernova can impose a significant "natal kick" on the resulting compact object. If the compact object is in a binary, and the binary is not disrupted as a result of the kick, the imposed kick with pull the binary system, causing the system as a whole to move with significantly higher velocity compared to pre-supernova velocity (e.g., Atri et al., 2019; O'Doherty et al., 2023, and references therein).

The planned span of the GBTDS (4.5 yr, Penny et al., 2019) and its predicted precision in astrometry and capability in measurement of proper motion over the entire length of the survey (down to $\approx$ 10s of μas/yr) along with photometric time-domain coverage will allow identification of systems that may have experienced a supernova, host a BH or a NS and are thus moving at high velocity through the Galactic bulge. Number of high velocity systems potentially hosting compact objects identified via this method and survey will be very influential on our understanding of the BH and NS population in our Galaxy.

Identification of microlensing black holes As discussed in detail by Roman white paper by Lam et al., "*Characterizing the Galactic population of isolated black holes*", GBTDS provides the only opportunity in the coming decades to identify the largest sample of isolated black holes in our Galaxy, with a prediction of at least 300 isolated black holes to be discovered by the GBTDS. It is worth noting that at the moment, we know of only a single confirmed isolated black hole in our Galaxy (Lam et al., 2022; Sahu et al., 2022) and approximately a dozen candidates (Wyrzykowski & Mandel, 2020). Thus, discovery of at least 300 new isolated black holes, will boost the sample by a factor of 20, a ground-breaking advancement in our understanding of isolated black holes in our Galaxy.

Discovery of new isolated BHs, combined with identification of new black holes in binaries with the GBTDS, paves the path to a unique and thorough observational view of the black hole population of our Galaxy for the first time.

3 Importance and impact of covering the inner bulge and Galactic center with the GBTDS

The Galactic bulge, and particularly the inner ~ 100 pc (corresponding to a radius of $\approx 0.6°$), harbors a large population of compact objects in binaries and energetic transients. Near-infrared observations have been crucial in understanding the nature of these systems (e.g., Wevers et al., 2016; Shaw et al., 2020) and characterizing their population and evolution of accreting binaries containing compact objects. However, such studies have been done as targeted follow-ups with heavily constrained scope. In contrast, the GBTDS will enable study of thousands of energetic systems in the Galactic bulge.

It is in this context that maximizing the overlap of GBTDS with existing X-ray surveys plays a significant role. The Galactic center and bulge are among the most observed parts of the sky in the X-rays with a vast array of observatories including (but not limited to) *Chandra*, *Swift*, *INTEGRAL*, *XMM-Newton*. These X-ray observations have led to discovery of more than 15,000 X-ray sources within the inner 4-degree-squared area of the Galaxy (e.g., Evans et al., 2019). In Figure 1, we compare the currently planned fields for the GBTDS (based on Penny et al. 2019) to existing coverage of the Galactic bulge by *Chandra* and *Swift*. *Chandra* surveys of the Galactic bulge and Galactic center have revealed thousands of X-ray sources in these regions. *Swift* Galactic Center monitoring on a weekly/daily basis has been ongoing since 2006, leading to discovery of numerous new transients (Degenaar & Wijnands, 2010), in addition to a unqiue long-term view of Sgr A* (Andrés et al., 2022).

In Figure 1, we also demonstrate an example of a minimally-modified plan for the GBTDS to increase the overlap with existing surveys (right panels). The example plan demonstrated in the right panels of Figure 1 will increase the number of cataloged *Chandra* X-ray sources from 1700 (under the current GBTDS plan) to 7800. This is a significant enhancement, enabling a large systematic study of X-ray binaries and transients.

4 Summary and concluding remarks

- The Roman GBTDS enables deep explorations of some of the most fundamental questions in astrophysics of black holes, neutron stars and accretion around these compact objects.
- These include first ever deep and wide view of some of the hidden subpopulation of black holes and neutron stars in the Galaxy. Along with ongoing X-ray monitors and surveys of the region, the multi-year span of the survey will provide an in-depth multi-wavelength view of accretion phenomenology in X-ray binaries.
- GBTDS observations with the F146 filter are vital to access stellar content of the Galactic bulge, particularly underluminous counterparts of X-ray binaries.

- Increasing overlap of GBTDS planned fields with previous X-ray coverage of the Galactic bulge and Galactic center provides a significant boot in scientific exploration of compact objects in our Galaxy, namely an increase in number of covered known *Chandra* X-ray sources in the region from 1700 to 7800.

Synergy with other Roman white papers

- **Importance of coverage for the inner bulge and Galactic center to enhance scientific outcomes** Coverage of the inner bulge and the Galactic center enhances scientific studies of compact objects in binaries and energetic transiently significantly. However, these domains are not alone in benefit from such coverage. As pointed out by Roman white paper by Terry et al., "*The Galactic Center with Roman*" such a coverage would enable study of local area of Sgr A* with significant benefits in multiple areas of study such as evolution of galactic nuclei and co-evolution with the growth of the supermassive black hole, monitoring the accretion onto the central supermassive black hole and dynamics of stellar populations in the heart of our Galaxy.

- **Ground-breaking view of the black hole content of our Galaxy** While it is estimated that our Galaxy harbors $\approx 10^6$ to 10^8 BHs, the number of observed Galactic black holes is currently < 100. Roman white paper by Lam et al., "*Characterizing the Galactic population of isolated black holes*" details the GBTDS potential to discover isolated black holes in our Galaxy. In this white paper, we have described the survey potential to discover new black holes in binary systems. GBTDS will enable discovery of hundreds of new BHs, isolated or in binaries, enabling a significant shift in our understanding of the BH population, and their formation in our Galaxy.

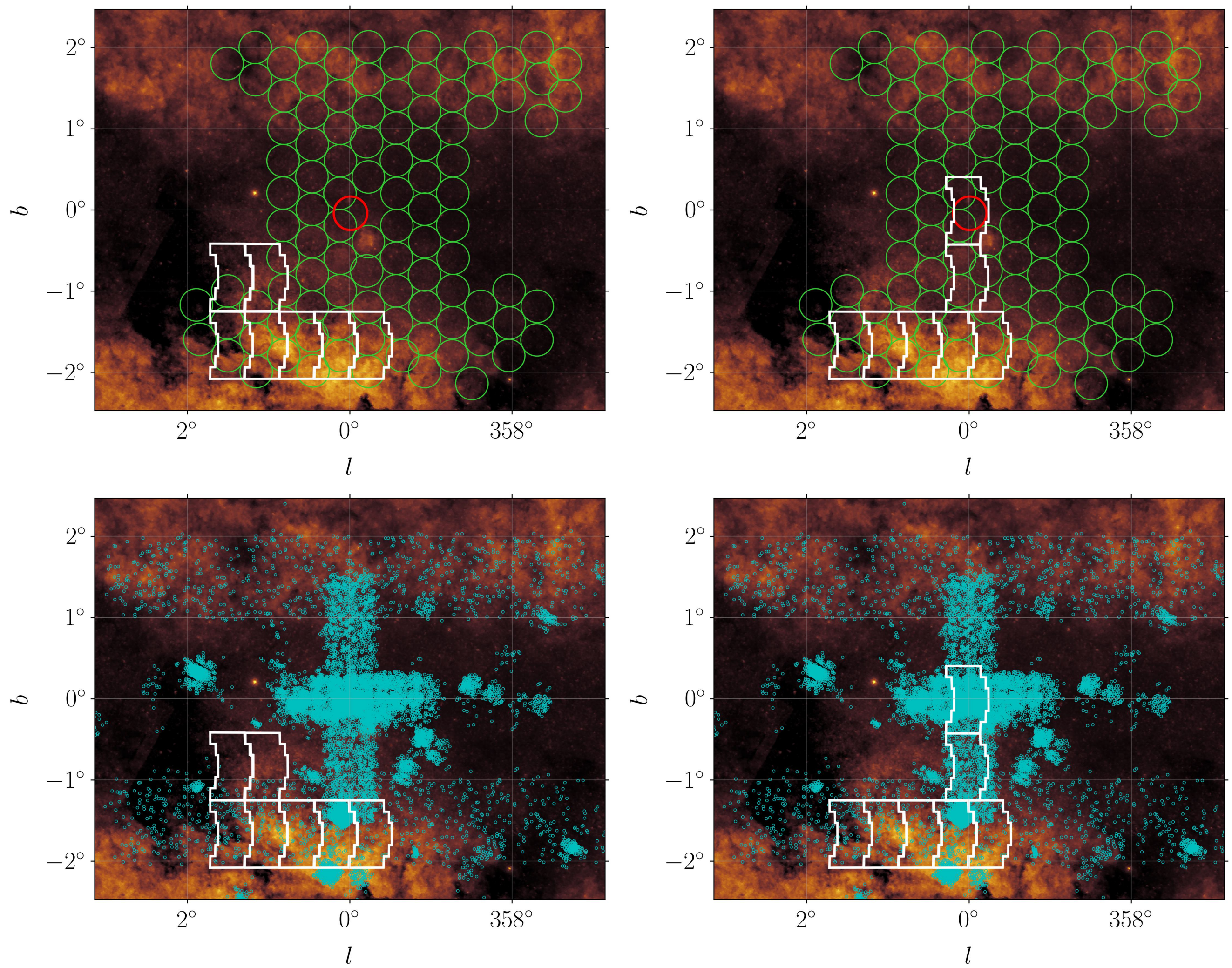

Figure 1: DSS view of the Galactic bulge. White polygons represent the field of view of *Roman*/WFI, with the notional fields of the GBTDS (left panels) based on Penny et al. (2019) and a possible re-adjustment of the fields to enhance overlap with existing X-ray surveys and cover the Galactic center (right panels). Green circles in the top panels represent coverage over the past 6 years with the *Swift* Galactic Bulge Survey (Shaw et al., 2020; Bahramian et al., 2021), while the red circle represents *Swift* weekly/daily monitoring of the Galactic center which has been continuing since 2006 (Degenaar et al., 2015). Cyan circles in the bottom panel represent *Chandra* X-ray sources from the Chandra Source Catalog (version 2; Evans et al., 2020), which are in large part a result of coverage by surveys such as *Chandra* GBS (Jonker et al., 2014; Grindlay et al., 2011; Muno et al., 2009). **The plan proposed in this work (the right panels) will cover 7800 cataloged *Chandra* X-ray sources, compared to 1700 covered by the notional GBTDS plan.**

References

Andrés, A., van den Eijnden, J., Degenaar, N., et al. 2022, MNRAS, 510, 2851
Arnason, R. M., Papei, H., Barmby, P., Bahramian, A., & Gorski, M. D. 2021, MNRAS, 502, 5455
Atri, P., Miller-Jones, J. C. A., Bahramian, A., et al. 2019, MNRAS, 489, 3116
Bahramian, A., Heinke, C. O., Kennea, J. A., et al. 2021, MNRAS, 501, 2790
Degenaar, N., Linares, M., Altamirano, D., & Wijnands, R. 2012, ApJ, 759, 8
Degenaar, N., & Wijnands, R. 2009, A&A, 495, 547
—. 2010, A&A, 524, A69
Degenaar, N., Wijnands, R., Miller, J. M., et al. 2015, Journal of High Energy Astrophysics, 7, 137
Evans, I. N., Allen, C., Anderson, C. S., et al. 2019, in AAS/High Energy Astrophysics Division, AAS/High Energy Astrophysics Division, 114.01
Evans, I. N., Primini, F. A., Miller, J. B., et al. 2020, in American Astronomical Society Meeting Abstracts, Vol. 235, American Astronomical Society Meeting Abstracts #235, 154.05
Gomel, R., Faigler, S., Mazeh, T., & Pawlak, M. 2021, MNRAS, 504, 5907
Gomel, R., Mazeh, T., Faigler, S., et al. 2022, arXiv e-prints, arXiv:2206.06032
Goodwin, A. J., Russell, D. M., Galloway, D. K., et al. 2020, MNRAS, 498, 3429
Grebenev, S. A., & Mereminskiy, I. A. 2015, Astronomy Letters, 41, 765
Grimm, H. J., Gilfanov, M., & Sunyaev, R. 2002, A&A, 391, 923
Grindlay, J. E., Hong, J., Servillat, M., et al. 2011, in American Astronomical Society Meeting Abstracts, Vol. 218, American Astronomical Society Meeting Abstracts #218, 122.06
Jayasinghe, T., Kochanek, C. S., Stanek, K. Z., et al. 2018, MNRAS, 477, 3145
Jonker, P. G., Bassa, C. G., Nelemans, G., et al. 2011, The Astrophysical Journal Supplement Series, 194, 18
Jonker, P. G., Torres, M. A. P., Hynes, R. I., et al. 2014, ApJS, 210, 18
Kuulkers, E., Shaw, S. E., Paizis, A., et al. 2007, A&A, 466, 595
Lam, C. Y., Lu, J. R., Udalski, A., et al. 2022, ApJ, 933, L23
Liu, X. W., & Li, X. D. 2006, A&A, 449, 135
Maccarone, T. J., & Patruno, A. 2013, MNRAS, 428, 1335
Muno, M. P., Bauer, F. E., Bandyopadhyay, R. M., & Wang, Q. D. 2006, ApJS, 165, 173
Muno, M. P., Pfahl, E., Baganoff, F. K., et al. 2005, ApJ, 622, L113
Muno, M. P., Bauer, F. E., Baganoff, F. K., et al. 2009, ApJS, 181, 110
O'Doherty, T. N., Bahramian, A., Miller-Jones, J. C. A., et al. 2023, MNRAS, 521, 2504
Penny, M. T., Gaudi, B. S., Kerins, E., et al. 2019, ApJS, 241, 3
Pfahl, E., Rappaport, S., & Podsiadlowski, P. 2002, ApJ, 573, 283
Ruiter, A. J., Belczynski, K., & Harrison, T. E. 2006, ApJ, 640, L167
Sahu, K. C., Anderson, J., Casertano, S., et al. 2022, ApJ, 933, 83
Shaw, A. W., Heinke, C. O., Maccarone, T. J., et al. 2020, arXiv e-prints, arXiv:2001.03683
Thompson, T. A., Kochanek, C. S., Stanek, K. Z., et al. 2020, Science, 368, eaba4356
Tucker, M. A., Shappee, B. J., Holoien, T. W. S., et al. 2018, ApJ, 867, L9
Wang, Q. D., Gotthelf, E. V., & Lang, C. C. 2002, Nature, 415, 148
Wevers, T., Hodgkin, S. T., Jonker, P. G., et al. 2016, MNRAS, 458, 4530
Wevers, T., Torres, M. A. P., Jonker, P. G., et al. 2017, MNRAS, 470, 4512
Wijnands, R., in't Zand, J. J. M., Rupen, M., et al. 2006, A&A, 449, 1117
Wyrzykowski, Ł., & Mandel, I. 2020, A&A, 636, A20
Zhu, Z., Li, Z., & Morris, M. R. 2018, ApJS, 235, 26