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THESEUS Science on Time-domain Studies of Compact Object Binaries

Şölen Balman,[a,*] **Sandro Mereghetti,**[b] **Julian P. Osborne**[c] **and**
On behalf of the Science Working Group on Time Domain Astronomy

[a] *Dept. of Astronomy and Space Sciences, Faculty of Science, Istanbul University, Beyazit, 34119, Istanbul, Turkey*

[b] *INAF, IASF-Milano, via A. Corti 12, I-20133 Milano, Italy*

[c] *School of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK*

E-mail: solen.balman@istanbul.edu.tr, solen.balman@gmail.com

THESEUS is a mission concept designed to survey transient events in the high-energies (0.3 – 10 MeV) across the whole sky and over the time scale of cosmic history. The mission aims to complete a panorama and census of gamma-ray bursts (GRBs) from the Universe's first billion years, and reconcile the life cycle of the first stars. THESEUS is expected to work on real-time triggers and follow accurate locations of sources, which may be used by other space- or ground-based telescopes operating at X-ray, Gamma-ray and other complementary wavelengths. The space observatory would study gamma-ray bursts (GRBs) and transient phenomena relating to X-ray and Gamma-ray sources (e.g., compact X-ray binaries) and their association with supernovae and novae including events like shock break-outs, black hole tidal disruption events, and magnetar flares. Compact X-ray binary sciences involve phenomena that deserve alerts and follow-ups where THESEUS will be fundamental. THESEUS is ideal to study accretion physics, accretion disks, outburst cycles, variability properties of compact X-ray binaries on different timescales for different classes of these systems. New sources and new states of sources will be recovered and the accumulated data over the years will be essential in explaining theoretical and observational controversies and complexities along with yielding new physics and theories.

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*Speaker

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1. Introduction

THESEUS has a goal to advance multi-messenger and time-domain astrophysics with a particular aim to exploit Gamma-Ray Burst events for investigating the early Universe [1–3]. THESEUS will work with a unique combination of instruments allowing GRB and X-ray transient detection over a broad field of view (> 1 sr) with 0.5-1 arc min localization, an energy band from several MeV down to 0.3 keV and a high sensitivity to transient sources in the soft X-ray domain, as well as on-board prompt (few minutes) follow-up with a 0.7 m class IR telescope with both imaging and spectroscopic capabilities [1, 4]. THESEUS will be providing research opportunities on open issues in cosmology, measuring star formation rate and metallicity evolution of the inter-stellar and intra-galactic medium up to redshift $\sim$ 10, it may be used to find signatures of Pop III stars, and shed light to physics of re-ionization. In addition, it will enable the study of variable X-ray sky, thus detecting, localizing, and identifying the electromagnetic counterparts to sources of gravitational radiation, detected in the late 2020s or 2030s by the next generation facilities like aLIGO/ aVirgo, eLISA, KAGRA, Cosmic Explorer and Einstein Telescope. THESEUS will be available along with the next generation multi-wavelength observatories (e.g., LSST, ELT, SKA, CTA, ATHENA) for studying thousands of faint to bright X-ray sources using the unique simultaneous availability of broadband X-ray and NIR observations [see also 5]. The mission will be equipped with fast positing for ToO capabilities and guest-observer programs providing monitor of fast transient events. In these regards, it is well-suited for studies of persistent and transient compact object binary sources [6].

The THESEUS payload includes several instruments to achieve the goals described above (Amati et al. 2021). The Soft X-ray Imager (SXI) is a set of two sensitive lobster-eye telescopes observing in 0.3–5 keV band with a total FOV of 31×61 deg^2 and source location accuracy $< 2'$. The X-Gamma ray Imaging Spectrometer (XGIS,) involves 2 coded-mask X-gamma ray cameras using Silicon drift detectors coupled with CsI crystal scintillator bars observing in 2 keV–10 MeV band and an FOV of 117×77 deg^2 (two cameras) overlapping with the SXI, with $<15'$ GRB location accuracy in the 2–150 keV band. THESEUS involves an IR telescope for simultaneous observations of the variable X-ray-to-Gamma-ray sky. InfraRed Telescope (IRT) is a 0.7 m class IR telescope observing in the 700-1800 nm band, providing a $15'\times15'$ FOV, with both imaging and moderate resolution spectroscopy capabilities (R=400). The limiting sensitivity is between 20.4-20.9 mag, while the localization capability $< 1''$. The satellite will have a Low Earth Orbit ($<5^\circ$, 600 km, 96.7 min.) with Autonomous rapid slewing bus (>10 deg/min) with a 4-year nominal mission time including possible extension of several years. THESEUS observing strategy will result in a non-uniform sky coverage (Fig. 1). Sources in regions close to the pointing directions will be observed with a high cadence about 15 times per day, for periods of visibility lasting from a few weeks to a few months, depending on their position. Most of the Survey Mode pointings will have a duration of about 2.3 ks. The satellite pointings resulting from GRB triggers will typically have a longer duration and a more uniform sky distribution in the sky. SXI and XGIS sensitivity versus exposure time is given in Fig. 2 left and right hand panels, respectively.

THESEUS aims to provide rapid alerts to enable triggered observations with other facilities. Such alerts will come not only from the discovery of new sources, but also from the detection of peculiar states in known sources that will be regularly monitored. Galactic X-ray binaries containing

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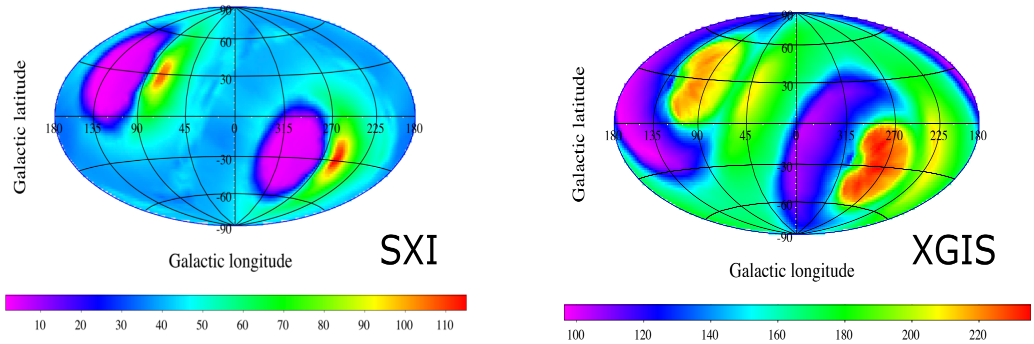

Figure 1: Expected Sky coverage during the 4-year mission given in days.

compact objects provide a panorama of different phenomena for which the alerts (and in many cases also the subsequent follow-up) with THESEUS will be essential. The soft and hard X-ray transients containing NSs (Neutron Stars), BHs (Black Holes), or WDs (White Dwarfs), outbursts from novae, thermonuclear super-bursts in low mass XRB, transitional accreting millisecond pulsars, and SFXTs are some objects where THESEUS may be the key to resolve fundamental issues. THESEUS will have the sensitivity to detect also the Very faint X-ray transients, a class of sources reaching only lower peak luminosities ($< 10^{36}$ erg s^{-1}) and of still unknown nature. Other classes of Galactic sources for which THESEUS triggers will be fundamental include stars undergoing super-flares and magnetars. Thanks to the large field of view of THESEUS's instruments and its observing strategy, a wide energy band coverage and high sensitivity will be combined with a long and high-cadence coverage of individual sources. This will enable the simultaneous analysis of broadband spectral variability, yield important information about accretion physics on WDs and NSs in Galactic X-ray binaries, as well as on black holes on all mass scales from stellar to super massive. Several classes of sources will be studied thanks to the observations of large samples, enabling systematic studies of their spectral-variability properties. *A detailed elaboration and discussion of the compact object sciences with THESEUS can be found in [6] along with all the figures presented in this proceeding.*

2. White Dwarf X-ray Binaries

Accreting White Dwarf Binaries (AWBs) host a primary WD and have a main sequence (MS) or a giant secondary star [7]. Magnetism of the WD is an essential ingredient determining accretion geometry. While AWBs spend most of their active lives powered by accretion, accumulation of accreted gas can result in a thermonuclear runaway and a nova outburst. Cataclysmic Variables (CVs) are close interacting binaries with MS secondaries where $P_{orb} \leq$15 hrs (some 2-2.5 d periods exist). They accrete via Roche Lobe (RL) overflow. Symbiotics systems have giant secondaries with several 100 d to 100 yrs binary periods and show mostly wind accretion with intervening disk accretion. AM CVn systems have orbital periods of 5 to 65 min with either RL overflow or stream impact accretion. Several CV subclasses exist [8]. The systems with weakly (or no) magnetic WD (B<0.01 MG) are referred as nonmagnetic CVs with subclasses of Dwarf Novae (DNe), Nova-likes (NLs). Magnetic CVs (MCVs) have WDs with field strength of 10 MG< B<230 MG. Several subclasses exist for other AWBs in general portraying high and low states, flares, active phases

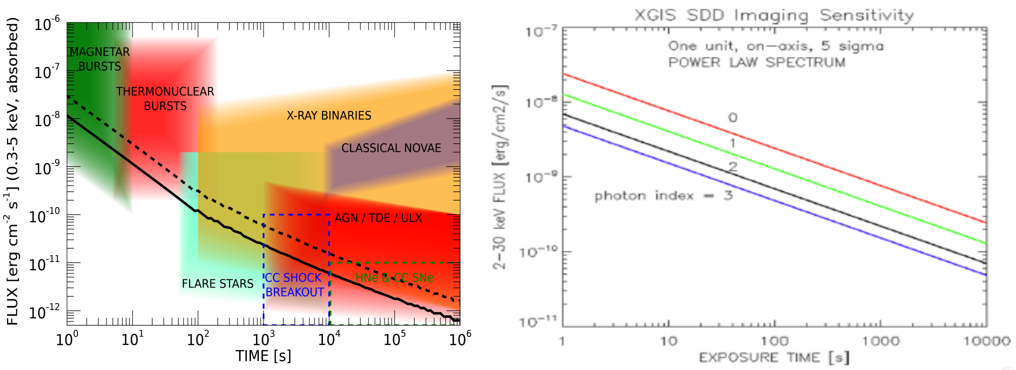

Figure 2: SXI sensitivity vs. exposure time on the right hand panel. Two models are used : power law, Γ=2 with N_H=5×10^{20} cm^{-2} (solid line) and N_H=10^{22} cm^{-2} (dashed line). Curves refer to absorbed flux in 0.3-5 keV with 95% confidence level for detection at 3σ. It acquires a good sensitivity at 10^{-10} erg cm^{-2} s^{-1} in 100 s, 2×10^{-11} erg cm^{-2} s^{-1} in 1500 s. On the right hand panel is the XGIS sensitivity (2-30 keV) for different exposure times (5σ confidence level detection; ΔE/E=1). Curves refer to a single unit and sources in the fully coded field of view (~10×10 deg^2).

(e.g., symbiotics), thermonuclear outbursts (i.e., nova events) to DN disk outbursts. Different types of outbursts/active phases, mass ejection and outflows frame current research interests where THESESUS will be fundamental.

2.1 MCVs with THESEUS

MCVs are AWBs that host magnetic WDs and their classification depend on the strength of the B field and synchronization of the binary and spin period of the WDs. Systems with 5-30 MG WDs are called intermediate polars (IP) and 20-230 MG are named polars [see reviews by 9, 10]. A stand-off shock occurs near the magnetic poles of the WD emitting X-rays with Bremstrahlung cooling (kT_{max}=10-50 keV; [11]) and/or Cyclotron cooling in the optical-to-IR. IPs are have disk-fed, stream-fed, or hybrid modes and Polars accrete via funnels to the poles of the WD which shows pole switching, mode changes, accretion geometry/topology changes [12–14]. X-ray Reflection is observed and polars show reprocessing induced soft X-ray components (blackbody with kT=20-60 eV). X-ray monitoring of high and low state changes and studies up to 100× difference may be provided by THESEUS. Over the mission life-time systematic collection of data will be acquired to study the response near the WD and geometrical changes to accretion rate variations from the donor [e.g., 15]. Timing and spectral analysis of accumulated THESEUS data will yield construction of WD mass distribution and physical models of accretion columns [see 11, 16]. Fig. 3 left hand panel shows a 25 ks simulation of an MCV (using SXI, XGIS) using a multi-temperature plasma model kT_{max}=45 keV and a Compton reflection component (extrapolated from parameters for NY Lup [17]). Assumed intrinsic hydrogen column density is N_H=5×10^{22} cm^{-2}. The bottom panel shows the residuals in standard deviations when the reflection component is excluded from the fit.

2.2 Nonmagnetic CVs and other AWBs

X-ray Observations from nonmagnetic CVs show several problems with the traditional models of X-ray emission depending on accretion rate from the standard boundary layers [18–21]. The

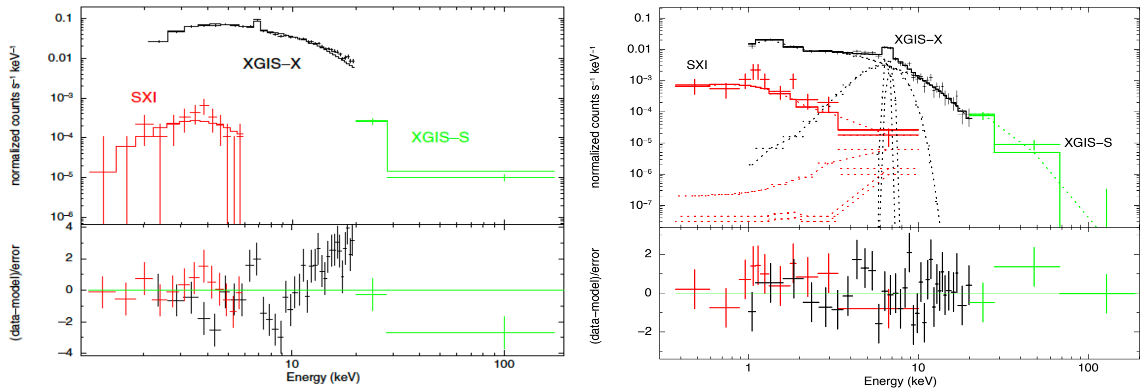

Figure 3: On the left is the 25 ks simulation of an MCV using a multi-temperature plasma model kT_{max}=45 keV and a Compton reflection component. Assumed intrinsic N_H=5×10^{22} cm^{-2}. The bottom panel shows the residuals in standard deviations when the reflection component is excluded from the fit. Rates are 0.0013 c/s (0.3-6 keV, SXI); 0.66 c/s (2-30 keV, XCIS-X); 0.0033 c/s (30-150 keV, XGIS-S). On the right hand panel is the 25 ksec simulation of a nonmagnetic CV using a multi-temperature plasma model kT_{max}=10 keV. Rates: 0.002 c/s (0.3-6 keV) – SXI 0.074 c/s (2-30 keV, XGIS-X); 0.0005 c/s (30-150 keV, XGIS-S).

controversies and complexities can be explained in the context of advective hot flows and dominating hard X-ray emission in quiescence, outbursts and high states [8, 22, 23, and references therein].

CVs show DN outbursts with duty cycles months to years, and durations of several days to weeks to months (L_x = 10^{30}-10^{33} erg s^{-1}). DN outbursts and duty cycles are explained in the context of Disk Instability Model – DIM [24, 25]. Several observational contradictions exists in the X-ray emissions with the DIM theory [8, and references therein]. Symbiotic or AM CVn systems show poorly categorized active phases that partly involve disk outbursts – AM CVns may have lower L_x values [26] , but Symbiotic's have L_x < several× 10^{34} erg s^{-1} [27]. THESEUS will be monitoring disk outbursts, their light curves and spectral evolution. The cadence of THESEUS and accumulated data will be unprecedented and will improve DIM theory and the existing observational controversies. THESEUS will enable systematic studies of high states, low states, and active phase for known or new AWBs. High state CVs (or AWBs) show mostly hard X-rays; better emission models or existence of power law tails that may yield from THESEUS surveys. THESEUS will provide first systematic/complete set of observations for X-ray spectral-timing studies (PDS versus spectra) of high state CVs together with all AWBs, QPOs, disk truncation and lag studies. As a result the true nature of the accretion flows and disk structure in CVs and AWBs can be revealed and studied [see also 28]. THESEUS will create a benchmark database to construct better models and theories. Fig. 3 right hand panel demonstrates a 25 ks exposure simulation (using SXI and XGIS) of a non-magnetic CV (extrapolated from parameters for BZ Cam, [23]) with a multi-temperature plasma model with a kT_{max}=10 keV and flux of 6×10^{-12} erg cm^{-2} s^{-1} flux in the 2-30 keV band.

2.3 THESEUS on nova outbursts and shock breakout

Nova outbursts result from thermonuclear runaways over the WD surface in AWBs where explosive H-burning yields one of the most luminous X-ray sources [29, 30]. Novae are possible SN Ia progenitors, and aid Galactic nucleosynthesis (Be, Li). X-ray emission of novae can have

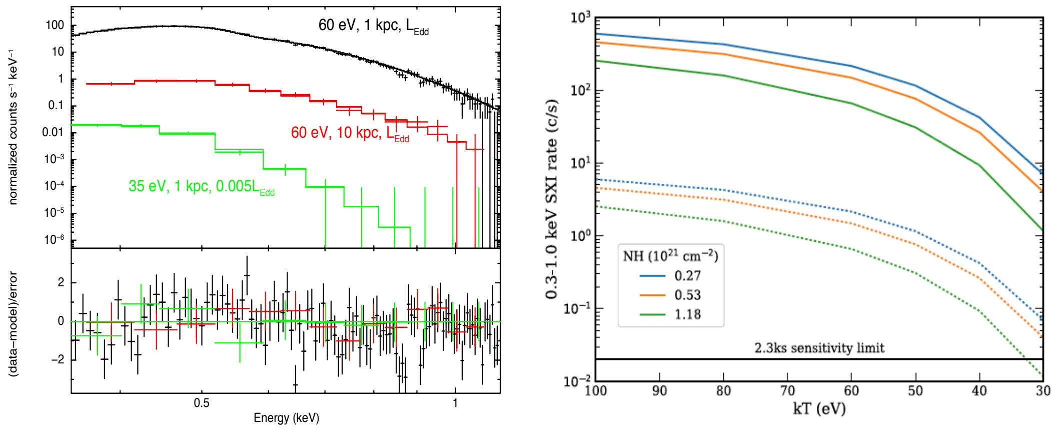

Figure 4: On the left is the SXI count rates for CN shock breakout [see the model in 36]. The upper curves are at 1 kpc and lower curves are at 10 kpc. Colors correspoond to different Galactic HI values. On the right is the SXI simulations of the Soft X-ray component. N_H is 2×10^{21} cm^{-2}, the WD effective temperature is 60 eV and d=1,10 kpc for a Eddington luminosity source (2500 s exposure) that yield 21.1 c/s and 0.22 c/s with SXI. Green-color spectrum corresponds to $0.005L_{Edd}$ for a 35 eV effective temperature to show the spectral quality after turn-off at 1 kpc (150 ks exposure).

several origins : 1) H-burning on the surface of the WD yield the super-soft X-ray component that last from days to years [31–34] 2) Ejecta interactions and resulting shocks yield the hard X-ray component. In addition, these interactions cause the particle acceleration prominent in GeV emission [35, and references therein] 3) In the first few hrs after the explosion, an extremely luminous soft X-ray source should be detectable. This is the 'fireball' phase at Eddington luminosity (L_{Edd}) which relates to the shock breakout. This is a short-lived phase ~hrs [36, and references therein]. Detecting the shock breakout needs sensitive, wide-field survey instruments where THESEUS SXI becomes essential (will have important implications on CN models and TNR theory). *eROSITA* has detected the first shock breakout in 2022 [37]. Fig. 4 shows SXI count rates for CN shock breakout. The peak temperature of the shock breakout is a measure of the mass of the WD; 100-30 eV corresponds to 1.3-0.6 $M_\odot$. In general, THESEUS will accomplish monitoring of soft and hard X-ray components of Novae using all detectors on board constraining e.g. WD temperature, mass, abundances, etc (see Fig.4 left hand panel for the soft component evolution). THESEUS will help to constrain shock physics, energetics of the ejecta and its morphology via synergies with *Fermi* LAT, *SKA*. *Swift*/XRT detects 18% of novae it observes at a rate of 0.4 c/s, these will be detected with THESEUS SXI at a 2 ks observation. Given a rate of 20-100 Galactic nova/year, we expect between 4-18 objects with THESEUS given that XGIS+SXI observes about 22% of the entire sky. A favorably positioned nova will receive multiple SXI pointings a day which will yield unique coverage of variability at short time scales during the SSS phase [38].

3. Neutron Star X-ray Binaries

Neutron star (NS) binary systems host primaries with magnetic field strengths 10^8 G<B<10^{15} G that in turn change the structure of the accretion flow channeling it to the magnetic poles of the NS. NS in these binaries spin very fast and are referred as XRPs (X-ray pulsars) [39, 40]. In weakly magnetized systems the magnetosphere can be smaller than the size of the NS (or a compact magnetosphere exists) so that the disk interacts with the NS surface. Weak or no pulsations are produced and systems are governed with the processes intrinsic to the disk. In more strongly magnetized binaries accretion and emission is determined by the B field and by the interaction of the plasma and radiation in presence of a strong B field. In general, When B > 10^{11} G (strongly magnetized NS), systems are young and massive (HMXBs) and when B < 10^{11} G (weakly magnetized) , they are older and have low masses (LMXBs). Both HMXBs & LMXBs include a large number of transients. These will be easily discovered and studied thanks to both the wide FOV and the wide spectral bandpass of the THESEUS mission.

3.1 High mass X-ray binaries

Within the HMXBs there are two types of transients of interest; Be X-ray Binaries (BeXRB) and Supergiant Fast X-ray Transients (SFXTs). SFXTs may show luminosity variability/changes up to factors of 10^6 and fast variability on minute time scales [41–43]. BeXRBs in outbursts show luminosities up to 10^{38-39} erg s^{-1} mostly during circumbinary disk passages with duration of several months. THESEUS will provide spectral and timing studies across luminosity variations and also shed light on the variability on short time scales and the evolution of the broadband continuum spectrum and the cyclotron features at high cadence. SFXT behave differently from persistent HMXBs due to either compact object and/or the accreting wind matter with low duty cycles and short flares [44]. THESEUS will enable the study of SFXT population at lower luminosities and sensitive broadband high cadence observations of this class. Continuous observation of transient XRPs (in HMXBs) with THESEUS (SXI/XGIS) (in a way similar to Fermi/GBM) will yield investigations of effects of plasma ionization state on NS spin-up/down processes; expand on the spin & orbital parameter determinations of more systems which will allow tracing of spin history of pulsars during outbursts and extrapolate to study fainter sources with lower pulsed fractions. A systematic study propeller effect in several HMXBs will be available by the THESEUS accumulated data sets [e.g., 45–47].

The magnetic field of XRPs can be determined through the observation of cyclotron lines E_{cyc}= 11.6 $B_{12}\times(1+z)^{-1}$ keV in the X-ray spectra, observed in about 35 sources, mostly transients [48]. THESEUS will expand this sample and provide better constraints on distribution of B fields in NS via continuous monitoring throughout outbursts. BeXRB indicate luminosity-dependence in E_{cyc} due to emission region geometry [49, 50]. Cyclotron line studies have been conducted during bright SFXT flares in the SXI range [51]. Known SFXTs will have 1 Ms to 10 Ms coverage in 4 yrs mission time of THESEUS which will allow the study of their flaring activity and their spectral (& orbital) evolution during this time. We calculate that SXI will detect 200-250 flares in 4 yrs.

3.2 LMXBs and accreting and transitional MSPs

NS LMXBs are weakly magnetized NS accreting from solar or sub-solar companions with orbital periods from tens of minutes to a few days. They show both transient or persistent behavior. There are several classes and sub-catagories among LMXBs; most relevant are Z- and atoll-sources [52]. LMXBs show spectral (and brightness) state changes, from Comptonized coronae to multi-color blackbody and blackbody from NS surface or boundary layers (BL). THESEUS will monitor the spectral evolution of almost the entire population of known persistent LMXBs during state

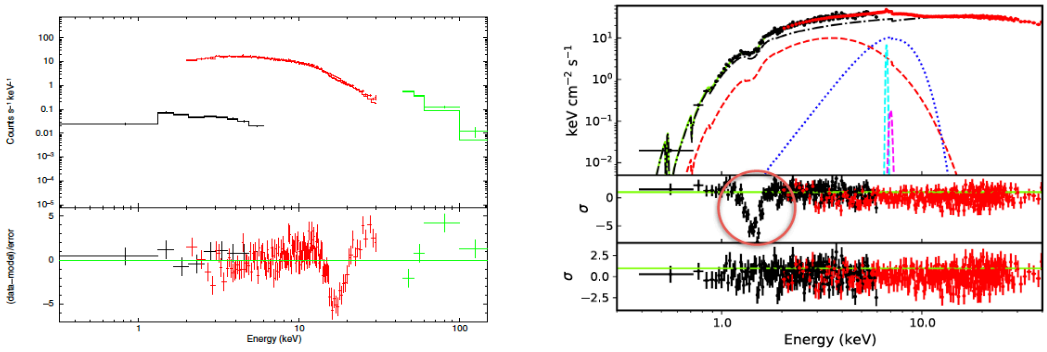

Figure 5: The left hand panel shows a 10 ks simulation of an SFXT spectrum in outburst. Model is cut-off power law and a cyclotron line at 17 keV. Residuals show a fit with no cyclotron line. The right hand panel displays a 2 ks simulation of a PULX (pulsar ultra-luminous X-ray source) in outburst $\sim 10^{39}$ erg s^{-1} (Swift J0243+61) with a proton cyclotron line at 1.45 keV for B=3×10^{14} G. (electron cyclotron lines can also be detected for 10^{11-15} G).

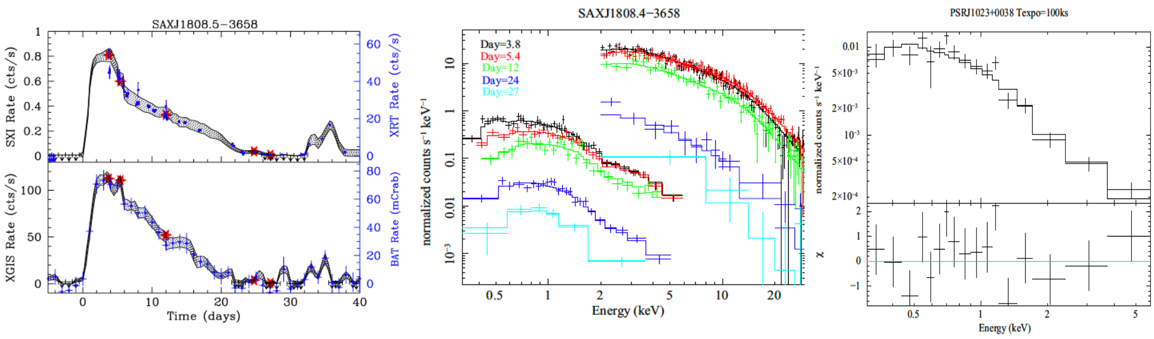

Figure 6: Simulated XGIS (2-30 keV) and SXI (0.3-6.0 keV) light curve of AMXP SAX J1808-36 in outburst (original values taken from [54]). THESEUS coverage when long up to 20-25 days will allow full light curves with reflares. XGIS and SXI spectra of the light curves on the left hand panel. Simulations are made for 2 ks for epochs 1-3, 30 ks for epoch 4, 100 ks ecpoch 5. A simulated SXI spectrum (100 ks) of PSR J1023+00, subluminous LMXB is shown on the right hand panel; an absorbed power law model is used.

changes along with the new discovered ones. In addition, it will be able to follow the low luminosity states owing to its high cadence of pointings during survey mode. Accreting millisecond X-ray pulsars, (AMXPs), are another class of LMXBs that harbor fast spinning NS (MSPs) with periods $\leq$ 30 ms, and are weakly magnetized (10^{8-9} G); about 1/3 of these MSPs show thermonuclear burst & oscillations [53].

Transient LMXB systems show occasional outbursts (L_x = 10^{34-38} erg s^{-1}) as they stay in quiescence most of the time (L_x = 10^{31-34} erg s^{-1}). THESEUS will catch the onset of outbursts from known and unknown sources and allow spectral and light curve coverage in high and low cadence depending on exposure times and the amount of times the source will be visited per coverage of the sky. In addition, synergy with other observatories and also the usage of IRT for simultaneous NIR wavelengths will be essential. Most transients behave as atolls, exceptions are

AMXPs that are rarely found in soft states in outbursts [53]. Some AMXPs also swing from accretion to rotation-powered states, called transitional pulsars. They are a link between LMXBs and RMSPs, rotation-powered pulsars [55]. These transitional pulsars appear in an intermediate sub-luminous state (L_x = 10^{33-34} erg s^{-1}) and change to a RMSP state. They are not found in outburst (only flares, low and high modes). These transitional pulsars are important laboratories for inflow, mass ejection in presence of moderate B [56]. There are several sub-luminous candidates for investigations using THESEUS.

THESEUS will monitor outburst evolution and catch state transitions of LMXBs in general allowing follow-up observations of transients with e.g., ATHENA, and ground-based optical & radio facilities. Among the MSP binaries in close orbits < 1 d, 65 AMXPs are known with 23 redbacks (companions low mass stars $0.1M_\odot$-$0.7M_\odot$), and 21 black widows (companion mass < $0.05_\odot$ and suffers irradiation erosion). THESEUS will detect at least 13 AMXPs entering into outburst with both SXI and XGIS. It will provide observing windows tens of days of full/partial coverage of outburst with 2 ks to 100 ks observation exposures (see Fig. 6 for a simulation). MSPs in sub-luminous state (transitional pulsars) , a 100 ks SXI observation yields detection, but not much is expected for rotation-powered state (which can be observed by other missions triggered with the monitoring of THESEUS). THESEUS will uncover state changes over a few weeks and monitor sub-luminous state for several years (see a simulated SXI spectrum in Fig. 6).

3.3 X-ray bursts and super-bursts

Accumulation of accreted material on the surface of NS (mostly atolls) triggers thermonuclear explosions. L_x increases by several orders of magnitude up to ~L_{Edd} during the so called Type-I bursts (few Type-II exist). Thermonuclear X-ray bursts are useful diagnostics of the equation of state and the compactness of NS [57–59], the nature of the companion star, and the distance to the system (assuming standard candles) [see 60]. The XGIS light curves and spectra (particularly on-axis) will allow for studying temporal variations, and the spectral parameter evolution for the X-ray bursts, particularly important for photospheric radius expansion bursts (PRE-bursts) (see Fig. 7). THESEUS will detect and permit the study of many Type-I bursts and super-bursts including time-resolved spectroscopy with possibly better time resolution than ever reached before. To-date about 115 LMXB bursters are known. THESEUS will catch hundreds of bursting events and allow for studies of population of the NS LMXBs with bursts. The expected rate of detection is 2.9-12.1 bursts/day. The 4-year time span is expected to yield 730 bursts (XGIS) and 150 of these are to be PRE-bursts (standard candles). Super-bursts (lasts ~ hours) are believed to be due to unstable C-burning. 25 super-bursts are detected from 15 LMXBs; generally persistent sources. THESEUS will provide timing and spectral resolution, the ASM instruments can not for these type of sources. We expect at least one super-burst per year with THESEUS (see Fig. 7).

3.4 LMXBs at high inclinations and very faint transients

The dip and eclipse arrival time studies of LMXB X-ray binaries at high inclinations (e.g, eclipsing systems) allow for determination of accurate orbital parameters and the orbital decay rates [62]. Such studies indicate super-Eddington accretion with non-conservative mass transfer [e.g., (14-22)% of the mass is transferred to NS 63, 64]. The large FOV of SXI and XGIS onboard

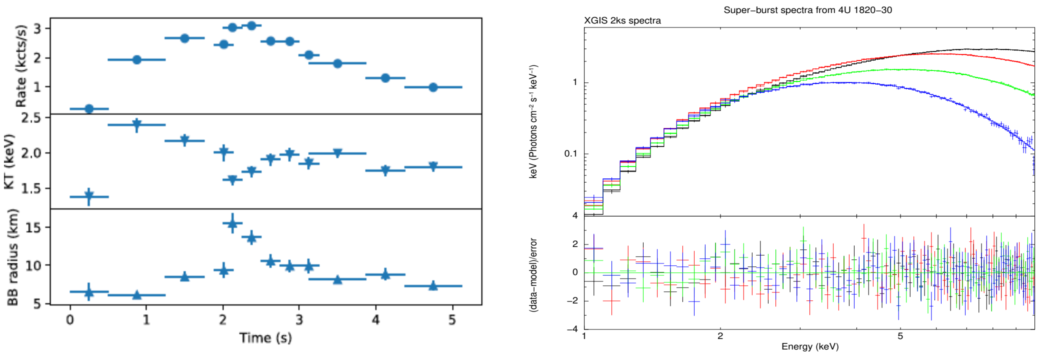

Figure 7: On the left hand panel, the high time-resolution spectral parameters of a PRE-burst is displayed calculated from simulated XGIS data [using data from 61]. On the right hand panel, a simulated XGIS time-resolved spectra shows a superburst cooling (each 2 ks).

THESEUS will permit the monitoring of light curves so that many other orbital solutions can be calculated or updated. THESEUS will allow possible triple system searches.

NS transient studies have revealed a group of Very Faint X-ray Transients (VFXTs). A small number of NS transients [65] exhibit long outbursts with peak L_x intermediate between outburst and quiescence $<10^{36}$ erg s^{-1} [66]; faint events in outburst. There are some interpretation for existence of these systems such as low mass-transfer rate, or experiencing later stages of evolution. THESEUS will enable studies of several new VFXTs for investigations of their nature. It will set the basis for follow-ups and provide simultaneous observations in the X-rays and IR (using IRT), where IR is essential for gathering information on donor stars.

4. Black Hole X-ray Binaries

Black Hole (BH) binaries, as with the name host BHs as primaries. About a dozen of such systems are persistent and thus they are mostly transient sources (BHTs). They show low luminosity in the quiescent state with $L_x \sim 10^{30}$ erg s^{-1}; during outbursts the luminosity increases to 10^{36-39} erg s^{-1} where the systems are observed to experience spectral state changes [67, 68], and show differing power spectral timing properties [69, 70]. This relates to accretion history and disk outbursts, explained in the context of DIM model as in DNe of CVs or irradiation driven effects. BHBs in the hard state show only a hard X-ray component, due to Compton up-scattering of soft-disk photons by a hot electron plasma which is the corona in the system at a temperature of around 100 keV. A weak soft component with an inner disk blackbody temperature $kT_{in} \sim 0.1$-0.3 keV appears as the accretion rate increases in the systems. The optically thick and geometrically thin disk [71] is well observed in high states attaining the highest luminosities (soft-state). In this state a strong disk component with $kT_{in} \sim 1$ keV can appear in the X-ray spectrum along with a steep power law $\Gamma >$ 2.5 extending out to 500 keV. Intermediate luminosity states also states exist.

THESEUS will carry out observations to disentangle main energy components of the the state changes (during the hysteresis) and follow the spectral evolution as a function of accretion flow (using its large FOV and broad energy range with all detectors). THESEUS will discover new BHTs adding to the 66 known systems with 132 outbursts, yielding 7-8 outbursts per year with durations

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~100 d [72, 73]. We expect about 2 new outburst/year with THESEUS adding to the above rate of detections. Synergy with ATHENA (X-ray), SKA (radio) , CTA (gamma-ray), accretion and ejection study of these transient sources can be well established. THESEUS provides simultaneous X-ray and NIR observations (NIR – traces X-ray emission) [74] as an indicator of jet activity in BHTs; [75–77]. THESEUS will permit study of jet-disk coupling, and the study of low ionization (cold) disk winds in the NIR during certain parts of the outburst. IRT of THESEUS will allow identification of deeply embedded optical counterparts and also study of quiescent properties of BHT population.

5. Ultra-Luminous X-ray Sources

ULXs are off-nuclear point sources with $L_x \geq 10^{39}$ erg s^{-1} exceeding the Eddington Limit for a 10 $M_\odot$ BH. Such systems host either a BH [stellar mass, 78–81] accreting above the Eddington limit, or a NS referred to as PULXs [about 6-7 objects, 82–85] where X-ray pulsations are detected indicating existence of super-Eddington accretion in NS binaries. The detection of X-ray pulsations in these systems clearly rule out a BH accretor. Several ULXs show spectral state variations with hard and soft components indicating soft or hard ultra-luminous states [see 86]. The standard ULX luminosity range is $10^{39} < L_x < 10^{41}$ erg s^{-1}. ULXs with luminosities higher than this are not common, and referred as HLXs (these may host IMBHs), but their vast distance of 4-95 Mpc makes them difficult to study as they show a common X-ray flux of around $\sim 10^{-12}$ erg cm^{-2} s^{-1}. THESEUS will closely monitor ULX/PULX systems and provide time-resolved spectroscopy at high cadence and long-term monitoring. It may reveal new ULXs that have high level of flux variability. Searches for nearby HLXs can be also conducted with THESEUS. SXI simulations indicate that in the 0.3-6.0 keV range (dominant range for ULXs), unabsorbed flux versus distance calculations, yield detection and study of most ULXs with standard luminosities using 2-500 ks exposures at distances $\leq$ 5 Mpc.

THESEUS survey and simultaneous IRT data (in the NIR) will enable studies of the IR counterparts of ULXs which will shed light into the evolutionary phases of the binary and the donor star [87]. The NIR analyses will reveal the nature and mass of each binary component which is still a current open issue. It is believed that origin of optical and IR emissions araise from the donor or the accretion disk [88]. Optical emission from nearby ULXs is found to be dominated by reprocessed emission from an extended accretion disk that provides a red excess [89], thus long term X-ray and IRT survey data can reveal the origins of the IR emission and the excess. Studies of ULX counterparts also yield presence of red supergiants; ~15 such systems have been found [90]. THESEUS will not provide IR spectroscopy at such low magnitudes, but photometry will be feasible which can be used to search for periodicities, orbital and super-orbital periods.

6. THESEUS Prospects for Compact Objects and Concluding Remarks

THESEUS combines large FOV instruments, with a unique observing strategy, using a wide energy band and high sensitivity providing a long and high-cadence coverage for individual sources. Higher overall sensitivity compared to the already operating facilities of its type, allow variability studies simultaneously over a wide energy band and on time scales and flux levels that have not

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been accessible previously. This is suitable to study accretion physics, accretion disks, outburst cycles, variability properties on different timescales of particular classes of XRBs.

The soft and hard X-ray transients (NS, BH), active states of AWBs, Novae and DN outbursts, thermonuclear super-bursts (LMXB), AMXPs, transitional accreting MSPs, and the SFXTs will be easily accessed by THESEUS via their high luminosities that enable detailed studies. Moreover, THESEUS will allow studies in quiescent and sub-luminous states of X-ray transients by accumulating data through the survey mode. Moreover, the VFXTs, quiescent and low states in CVs/AWBs, can be studied in this manner, as well. We expect that the 4-year survey time-span, will permit for the first time, adequate studies of photon-starved compact object systems utilizing the accumulated data in the long run. This will, in turn, yield better population synthesis studies and models. We expect that many new sources, and new peculiar state of sources will be revealed. THESEUS aims to provide rapid alerts to trigger observations with other space- or ground-based facilities and compact binary sciences involve phenomena that needs alerts and follow-ups where THESEUS will be very important. The space-based NIR telescope (IRT) on THESEUS will provide simultaneous spectroscopy and brightness measurements along with the X-ray surveys, e.g,, to study wind structures, outflows and ejections, and secondary star characteristics in compact X-ray binaries. The accumulated database of THESEUS will mediate fundamental science studies for investigating, e.g., new theoretical frameworks for accretion physics onto WDs, and new models that will resolve the interaction between accretion flows and NS magnetospheres. The detailed observational studies that will be conduced (at moderate spectral and at high time-resolution) of accretion phase-changes across compact X-ray binaries will yield new ecliptic theories/models for accretion flows, disk structure and ejection mechanisms.

Overall, wide fields of view and high sensitivity of SXI and XGIS instruments offer a great opportunity to study all classes of Galactic and extra-Galactic variable X-ray sources. The large FOV will yield unprecedentedly frequent long-term monitoring of sources that will yield studies on previously unattained timescales that can give access to physical processes which might have been missed. High cadence of the survey mode will enable discovery of rapid phenomena and broadcast that to the World and to other facilities for immediate follow-up that may result in new source types and states. The wide energy range provides a new opportunity to constrain the geometrical models and emission processes at work. The high sensitivity will expand the classes of high energy emitters. The use of IRT broadens scope and provides multi-wavelength monitoring including interesting targets for a GO program.

7. Conference Discussion

Dheeraj Pasham : How many other missions are competing with THESEUS at the moment ?
Şölen Balman : The number is five till mid-November 2023 at which time the next phase selection will be completed. At the time this proceedings is written, THESEUS is selected for the next Phase-A studies for 2.5 yrs along with only two other M7 mission candidates.

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