Science with the Daksha High Energy Transients Mission

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Abstract

We present the science case for the proposed *Daksha* high energy transients mission. *Daksha* will comprise of two satellites covering the entire sky from 1 keV to $>\mathbf{1}$ MeV. The primary objectives of the mission are to discover and characterize electromagnetic counterparts to gravitational wave source; and to study Gamma Ray Bursts (GRBs). *Daksha* is a versatile all-sky monitor that can address a wide variety of science cases. With its broadband spectral response, high sensitivity, and continuous all-sky coverage, it will discover fainter and rarer sources than any other existing or proposed mission. *Daksha* can make key strides in GRB research with polarization studies, prompt soft spectroscopy, and fine time-resolved spectral studies. *Daksha* will provide continuous monitoring of X-ray pulsars. It will detect magnetar outbursts and high energy counterparts to Fast Radio Bursts. Using Earth occultation to measure source fluxes, the two satellites together will obtain daily flux measurements of bright hard X-ray sources including active galactic nuclei, X-ray binaries, and slow transients like Novae. Correlation studies between the two satellites can be used to probe primordial black holes through lensing. *Daksha* will have a set of detectors continuously pointing towards the Sun, providing excellent hard X-ray monitoring data. Closer to home, the high sensitivity and time resolution of *Daksha* can be leveraged for the characterization of Terrestrial Gamma-ray Flashes.

Keywords: Space telescopes (1547) — Time domain astronomy (2109) — Gamma-ray bursts (629) — Gravitational wave astronomy (675)

1 Introduction

In the past decade, transient astronomy has received a great boost due to the expansion from electromagnetic (EM) regime to multi-messenger astronomy by including gravitational waves (GW), neutrinos, and high-energy cosmic rays. The joint detection of a faint gamma-ray burst (GRB) coincident with the gravitational wave detection of a binary neutron star (BNS) merger GW170817 [1, 2] was the first direct proof of the long hypothesized link between short GRBs and BNS mergers. This has also provided us with a detailed understanding of the production of r-process elements in kilonovae [3, 4] and independent measurements of the neutron star equation of state [5].

The GRB counterpart of GW170817, however, was several orders of magnitude fainter than expected than "classical" GRBs and was barely detected by most current space-based detectors [6]. With the improved sensitivity of advanced GW detectors, the horizon for detecting compact binary mergers involving neutron stars (possibly with a stellar mass black hole companion) will reach farther distances. We will need comparable improvements in X-ray and gamma-ray telescope sensitivities to be able to fully leverage the increased number of GW detections. Indeed, after GW170817 (at a distance of 40 Mpc), the BNS and neutron star black hole (NSBH) events detected in LIGO–Virgo observing run 3 (O3) where typically at distances $\gtrsim$ 100 Mpc. Despite extensive searches, no EM counterparts were found [see for instance 7, 8]. Roughly scaling the flux from GW170817 to these distances, the non-detections are not unexpected with the current sensitivity of all-sky missions.

X-ray and gamma-ray transient astronomy has been a rich field with missions such as *BATSE* [9, 10], *BeppoSAX* [11], *Swift* [12, 13] and *Fermi* [14] leading the exploration of GRBs, magnetar flares, and X-ray binary outbursts. More recently, instruments such as *AstroSat* CZTI [15], POLAR [16], and IKAROS-GAP [17] have characterized the polarization of GRBs. Yet, there remain open questions about the detailed emission mechanism, the jet launching physics, jet composition, the effects of magnetic fields, and the nature of the remnant and the afterglow [18, 19].

The next generation of transient detection telescopes need to have a much higher sensitivity and all-sky coverage to match the nearly isotropic visibility and detection horizons of GW detector networks — aLIGO [20], adVirgo

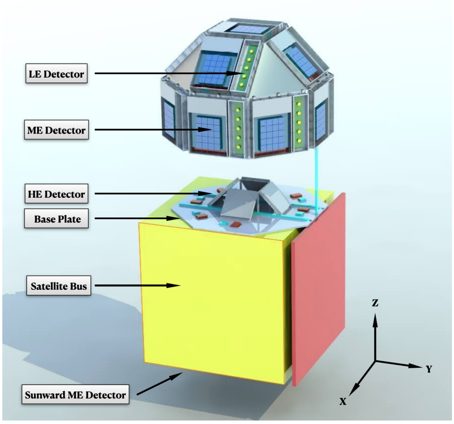

Fig. 1 Overall design of a *Daksha* satellite. The dome-shaped payload has 13 surfaces, each carrying Low-energy (LE) and Medium-energy (ME) detector packages. Four ME detector packages are mounted under the satellite bus, and always point directly to the sun. Four High-energy (HE) detector packages are mounted inside the dome, along with processing electronics.

[21], KAGRA [22], and LIGO-India [23, 24]. These should also provide low-latency alerts in order to coordinate with new synoptic radio, optical and infrared telescopes that will coordinate the EM followup response such as the ZTF [25], Rubin Observatory [26], Square Kilometer Array [27], uGMRT [28], LOFAR [29], ASKAP [30], and IceCube [31]. A greater sensitivity, especially at lower energies will improve detection rates of high-redshift GRBs, improving their use as probes of cosmology, star formation rates etc.

With these considerations, we have proposed *Daksha*, a broadband high-energy all-sky mission dedicated to X-ray and gamma-ray transient astronomy. In this paper, we discuss the science cases enabled by *Daksha*. The technical details of *Daksha* are given in a companion paper (Bhalerao et al, hereafter Paper I), but we have included a brief summary in Section 2 for completeness. In the next sections, we discuss the primary and secondary science enabled by *Daksha* along with the detection rate estimates and simulations — Section 3 covers the impact of *Daksha* for coincident detections of prompt GRB-like counterparts of GW events expected from upcoming gravitational wave detector networks; Section 4 covers the detection rates, prompt soft spectra, and polarization of GRBs; Section 5 covers the secondary science cases — X-ray pulsars, magnetar flares, fast radio burst (FRB) counterparts, primordial blackholes (PBHs), Earth occultation studies of bright X-ray sources, solar physics, and terrestrial gamma-ray flares.

2 Mission overview

The mission comprises of two satellites launched in a near-equatorial low-earth orbit (LEO). The pair of satellites located opposite to each other in their orbit helps to gain all-sky coverage by mitigating the impact of the South

Atlantic Anomaly and earth occultation in LEO. *Daksha* satellites use three types of detectors to cover an energy range from 1 keV to > 1 MeV (Figure 1). Silicon Drift Detectors (SDDs) cover the Low Energy (LE) range from 1–30 keV. Cadmium Zinc Telluride (CZT) detectors provide Medium Energy (ME) coverage from 20–200 keV. High Energy (HE) sensitivity is provided by NaI detectors with Silicon Photomultipliers, sensitive from 100 keV to > 1 MeV. Details of the instruments and their capabilities are given in Paper I.

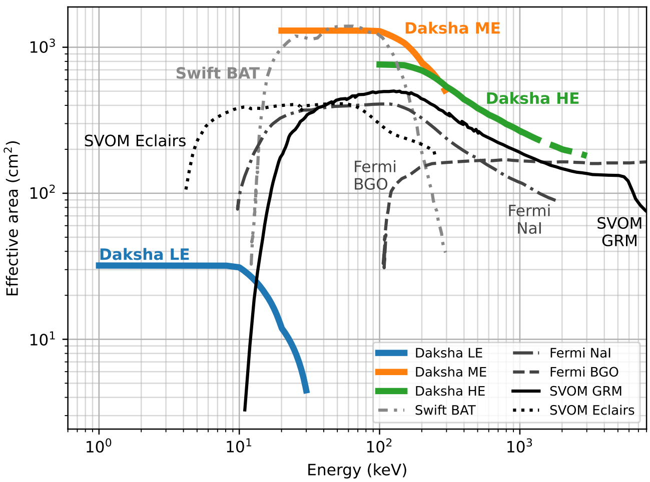

Fig. 2 Effective area of *Daksha* detectors as a function of energy. Effective areas of *Swift*-BAT and both NaI and BGO detectors of *Fermi*-GBM are shown for comparison. These areas were adapted from [32]. The NaI effective area is the averaged over the unocculted sky.

The workhorse of *Daksha* are the ME detectors, which provide nearly uniform all-sky coverage with a median effective area of ~ 1300 cm^2 (Figure 2), and a 5-σ sensitivity of 4×10^{-8} erg cm^{-2} s^{-1} for 1-second bursts. Bursts with fluence of about 1×10^{-7} erg cm^{-2} can be localized with an accuracy of 10°, with sub-degree localization for brighter bursts.

3 Science Driver I: Electromagnetic Counterparts to Gravitational Wave Sources

On 2017 August 17, gravitational wave detectors had the first direct detection of coalescing neutron stars. 1.7 s later, a flash of gamma rays was detected by *Fermi* and *Integral* missions [1, 2]. The high energy detection spurred broadband follow-up observations leading to the discovery of a kilonova [33], and eventually proving that the merger produced a successful structured jet [34–36]. Thanks to an extensive multi-wavelength data set, significant progress was made on many unsolved mysteries — proving the connection between neutron star mergers and short GRBs [37], establishing that such mergers indeed are the sites of r-process nucleosynthesis [38, 39], providing an independent measurement of the Hubble constant [40], and a measurement of the equation of state of ultra-dense matter [41, 42].

GRB 170817 was peculiar in many ways. It was detected further off axis than typical GRBs [35, 43, 44]. The prompt emission had soft spectral components which could not be adequately characterized or explained [37]. While it is the closest GRB ever detected, it was still faint — and intrinsically the most sub-luminous of all short GRBs detected to date [6]. Had this event even been 30% fainter for instance, it would have been missed by several EM missions [45]. This is consistent with studies conducted in the third observing run of the advanced gravitational wave detectors (O3): while several neutron star merger events were detected in gravitational waves, no electromagnetic counterparts were found. A notable example is the lack of counterparts to BNS event GW190425 at a distance of ~ 150 Mpc [46, 47]. Besides sensitivity, GW170817 also underscored the importance of continuous all-sky coverage: sensitive missions like *Swift* [48] and *AstroSat* [4] could not detect the source as it was occulted by the Earth at that instant.

The peculiarity GRB170817A of having low luminosity but comparable peak energy as any standard SGRBs [49] posed additional questions: Does GRB170817A belong to a new, unexplored class of SGRBs? Do we need high soft X-ray sensitivity to detect and study this class of sources? How would they be different in terms of source distribution, energetics, spectral properties etc? Multi-wavelength and multi-messenger studies of more sources are critical for tackling these questions. Such observations can shed light on the SGRBs distribution as well as into the physics of SGRB jet structure, energetics [50, 51].

The interferometric GW detector network is constantly getting upgraded. In future observing runs, the Advanced LIGO-Virgo detectors will achieve the sensitive distance reach of ~ 200 Mpc [52]. Additional advanced detectors such as the Japanese detector KAGRA [53] and the LIGO-India [24] will make the network uniformly sensitive over the sky, with the localization capability up to ten square degrees [54, 55]. A growing number of BNS sources will be detected within a few hundred Mpc [56, 57]. To maximize the science returns from these detections, we need new higher sensitivity instruments with all–sky coverage [2, 58].

3.1 Design considerations for EMGW

Daksha has been designed keeping in mind the lessons learnt from the GW network observing runs and corresponding follow-up programs. Two key features of *Daksha* are the higher sensitivity and all-sky coverage, thanks to which we will detect far more events than other missions (Section 3.3). On-board algorithms will detect bursts, localize them, and create coarse light curves and spectra to be broadcast globally within ~ 1 minute of each event. This information will enable groups to prioritize their resources and start rapid follow-up observations.

All event-mode data will be downlinked on the next ground-station pass, to create improved data products. The broad spectral coverage will play a critical role in modeling spectral components of the prompt emission. A unique capability for *Daksha* is its low energy coverage for prompt soft emission, which we discuss in Section 3.2. For bright events, *Daksha* will also be able to measure polarization of the events, which is discussed in greater detail in the context of GRBs in Section 4.6. All bursts detected by *Daksha* can also be utilized for "triggered" searches in GW network data for corresponding GW signals. Our calculations show that this can give a significant boost to the number of binary neutron star events detected in GW (Section 3.3; also see Bhattacharjee et al. in prep).

3.2 Probing science of soft X-ray sources: the cocoon shock breakout model

A SGRB jet propagating inside the merger ejecta forms a cocoon, which eventually breaks out from the ejecta surface. The emission arising from the cocoon shock break-out is expected to be composed of an initial hard-spike followed by a soft-tail [59, 60]. The luminosity, duration, and spectral peak of the hard spike and soft tail depend on the ejecta structure as well as the jet properties such as the power, opening angle and time delay between the merger and jet launch.

For instance, the emission properties of GRB170817A can be explained with the cocoon shock breakout model with a breakout radius of $\sim 2\times10^{11}$ cm, a maximum ejecta velocity of $\sim 0.7c$ [59]. Although these values are expected to be different for different events, the emission properties must roughly satisfy a closure relation between the duration, total energy, and the temperature [61]. Thus, the cocoon breakout model can be tested by detecting more X-ray flashes associated with neutron star mergers. Furthermore, by modeling the emission properties, we will be able to obtain valuable information about the structure of merger ejecta and the jet formation in neutron star mergers. This in turn may allow us to constrain the equation of state (EOS) of neutron stars, since the ejecta profile in the fast tail is sensitive to the EOS [62, 63].

3.3 EMGW Rates

The rate of joint EMGW detections depends on the volumetric BNS merger rate $\mathcal{R}$, the source emission models, and sensitivities of the GW detector network and EM satellites. We estimated these rates by injecting BNS events uniformly randomly in co-moving volume, with random inclination, then calculating their detectability by the GW network as well as *Daksha*. A detailed set of calculations with a variety of emission models will be presented elsewhere (Bhattacharjee et al., in prep), but we give a quick overview and present the results here.

We consider a configuration where five GW detectors are operating at their full sensitivity: "A+" sensitivity for LIGO Hanford, Livingston, and India, "AdV" sensitivity for Advanced Virgo, and the standard design sensitivity for Kagra. Following [57], we assume that the detectors have a duty cycle of 70%, and an event is considered to be detected in gravitational waves if the network signal-to-noise ratio (SNR) is > 8. We take $\mathcal{R} = 320$ Gpc^{-3}yr^{-1} from [64].

First, we assume a simplistic EM model where every BNS merger has the same intrinsic luminosity as GW170817, independent of viewing angle[1]. We assume a "Comptonized" spectral model with a photon power-law index $\alpha = -0.62$, an exponential cut-off at $E_p = 185$ keV, duration $\Delta t = 0.576$ s [37]. The luminosity is calculated to match the observed Fermi flux of $3.1{\times}10^{-7}$ erg cm^{-2} s^{-1} in the 10–1000 keV band. Using the *Daksha* sensitivity discussed in Paper I, we calculate that the pair of *Daksha* satellites will detect about 0.5 neutron star merger events per year (after accounting for time lost due to SAA etc), almost all of which will have a high enough GW amplitude to be detected by GW networks.

Next, we consider a "Gaussian jet" model from [65], where the jet energy E_γ and the Lorentz factor Γ are given by,

$$E_\gamma(\theta) = \eta_\gamma E_0 e^{-\theta^2/2\theta_0^2} \tag{1}$$

$$\Gamma(\theta) = \Gamma_{\rm max}/(1 + (\theta/\theta_0)^\lambda) \tag{2}$$

where $\theta_0 = 0.059$ rad, $\Gamma_{\rm max} = 2000$ and $\eta_\gamma = 0.1$. The event duration was assumed to be 0.3 s for all the events, the typical sGRB duration [66]. Source energies (E_0) are drawn from the luminosity function given by [67]. For this model, we find that *Daksha* will obtain 12 joint detections with the GW network per year. On the other hand, very few events are found despite *Daksha*'s high sensitivity, the upper limits from our data will imply that gamma-ray production efficiency drops beyond the core: thereby giving new insights into the underlying dissipation and emission mechanisms [44].

Another key observation in the Gaussian jet simulations is the presence of several events that are clearly detectable by *Daksha*, but just below the GW network SNR of 8. Since the direction and time of the bursts will be known from *Daksha*, we can undertake sub-threshold searches for coincident GW events [see for instance 68, 69]. Considering such sub-threshold events to be detectable if their GW network SNR is > 6.5, we find that *Daksha* will enable the detection of gravitational waves from an additional seven sub-threshold neutron star mergers each year.

4 Science Driver II: Gamma Ray Burst science

The observed GRBs fall into two broad categories. They are long GRBs (LGRBs) with duration $T_{90} > 2$ sec and short GRBs (SGRBs) with $T_{90} < 2$ sec. Long GRBs are produced by the core collapse SNe of giant star [70–72], while, the short GRBs are produced by the merger of binary compact objects such as binary neutron stars and neutron star - black hole. The observation

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[1] This implies that there is no bright jet even for face-on observers.

of GW170817 confirmed that at least a class of short GRBs are produced by binary neutron star (BNS) mergers [73].

A typical GRB emission consists of two main parts: the *prompt* phase which consists of the immediate γ-rays produced closed to origin of the burst, and the late time *afterglow* phase which is produced as the outflow interacts with ISM surrounding the burst. The afterglow phase is well studied unlike the prompt phase. The GRB afterglow observations provide the redshift of the the burst which shed light on the constituents of ISM and the underlying physical processes [74–76]. The broadband observation of the afterglow phase conveys broad picture of the energetics and timeline of the underlying processes.

During the main prompt GRB phase, the source invokes highly relativistic jets with bulk Lorentz factors of a few hundreds emitting highly energetic photons. The exact physical mechanism producing such powerful γ-rays still remains debated [19]. The composition of GRB jets, the radiative processes giving rise to the prompt γ-rays are some of the open ended questions [19]. Both in terms of spectral properties and physical mechanisms, prompt emissions are still comparatively poorly explored [77] as opposed to the afterglow phase due to the transient nature of the event and lack of observations in the soft X-ray band [78, 79]. *Daksha* is expected to improve over both these aspects with its all-sky capability and ability to probe in soft X-ray band and hence improving the population of the GRBs. Owing to the high sensitivity, *Daksha* will help towards better understanding of the transition between the prompt and afterglow emission in GRBs. This is of high importance — for instance, it will enable the determination of the Lorentz factor of the external shocked region, and whether the deceleration is effectively in the "thick shell" or "thin shell" regimes. Below, we highlight on the GRB science we can probe with the *Daksha* mission especially in the prompt phase.

4.1 GRB Rates

The distribution of the rate of long gamma ray burst with respect to redshift, z, mainly depends on the star formation rate $R_{GRB}(z)$ and the luminosity function $\phi(L)$. In case of the distribution of the rate of short GRBs, an additional factor of time delay (Δt) relative to the star formation rate is also considered. We adopt a functional form of broken power law for both $R_{GRB}(z)$ and $\phi(L)$ as mentioned in Wanderman & Piran[80], whereas, a model of lognormal distribution is adopted for the time delay from Wanderman & Piran[81]. The various parameters defining $R_{GRB}(z)$, $\phi(L)$ and Δt are evaluated separately using the observed distribution of the redshift detected long and short GRBs by the *Swift* mission during the span of 17.5 years[2]. During this period, *Swift* has detected a total of 1314 long GRBs and 133 short GRBs, out of which 350 long GRBs and 26 short GRBs are found to have redshift measurements.

We use the *Swift* redshift distributions of long and short GRBs to predict GRB detection rate of *Daksha*. Using the obtained fit values and the *Daksha* sensitivity of $S = 4 \times 10^{-8}$ erg cm^{-2} s^{-1}and spatiotemporal coverage of

[2]Note Δt is estimated for the short GRB distribution only.

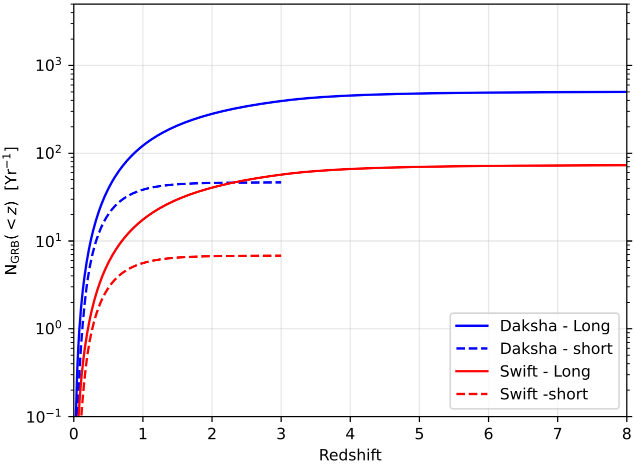

Fig. 3 The cumulative plot showing the long and short GRB detection rate (per year) the by *Daksha* and *Swift* as a function of redshift.

$\Omega T/(4\pi) = 87\%$ (Paper I), we estimate that *Daksha* can detect nearly 500 long GRBs and 46 short GRBs per year (around 7 and 2.5 times greater than current *Swift* and *Fermi* rates respectively). Figure 3 shows the expected redshift distribution for long and short GRB that would be observed by *Daksha*.

4.2 Broad-band spectroscopy of the prompt emission

The physical origin of the prompt emission in GRBs is still a subject of intense debate. In absence of a clear understanding of the processes giving rise to the prompt emission, its spectrum is typically characterized by an empirical model consisting of two smoothly joining power-law [10], known as Band model or Band function. The typical GRB spectra in νF_ν form, shows a peak around energy of $\sim$100 keV, characterized by the peak energy E_p, of the Band function. The spectra below and above E_p are characterized by two spectral indices α and β of the Band function. It has been observed that the peak energy is correlated to the isotropic equivalent energy of GRBs [82, 83]. Further, it has been found that the isotropic equivalent energy of the prompt emission is correlated with the Lorentz factor of the outflow [84, 85], which may define the other spectral parameters. Thus, accurate estimation of the GRB spectral parameters is important.

4.3 Prompt emission spectral anomaly with soft X-ray studies

A disagreement exists between the observed prompt spectral shape and the theoretical synchrotron predictions from a non-thermal population of ultra relativistic electrons in the soft X-ray band [86, 87]. The observed GRB prompt spectra consist of a photon index $\langle\alpha\rangle \sim -1$ which is on the harder side than the value $\alpha = -1.5$ expected from fast cooling synchrotron radiation. Unfortunately, the observational statistics for the existing missions in this low energy prompt phase are really poor.

Several explanations exist in literature to counter this discrepancy. One of the scenarios is either the cooling frequency ν_c or the self-absorption frequency ν_{sa} being comparable to the characteristic synchrotron frequency ν_m [87, 88]. Another possibility points at the low-energy part of the synchrotron spectrum being modified by the energy-dependent inverse Compton scattering in the Klein-Nishina regime hence hardening spectral shape (up to $\alpha = -2/3$) [89]. These models assume a constant magnetic field, while some other models explain the spectral hardening by invoking a non-uniform magnetic field that depends on the radius and/or the distance from the shock front [90]. Moreover, synchrotron spectra can have photon indices much harder than -1.5 if the pitch angles of the emitting electrons are distributed anisotropically [91]. It is then extremely important to explore whether these proposed scenarios represent a viable solution and are supported by observational evidence.

Oganesyan 2018[93] have characterized GRB prompt emission spectra down to soft X-rays; in their sample of about 34 GRBs, they detect a low energy break in about 62% of the spectra where the spectra harden below the break energy (between 3 keV and 22 keV in their sample). However, this sample is small, and *Daksha*, with its dedicated detector to measure the soft X-ray spectra of the prompt emission, is ideally suited to determine the low-energy break for large number GRBs. Figure 4 shows the simulated spectra of a GRBs with 10–1000 keV fluence of 1×10^{-5} erg cm^{-2} as as detected by *Daksha* and *Fermi*-GBM.

4.4 Extended emission and long central engine activity

A fraction of SGRBs are observed to have softer extended emission on time scales of a few seconds to a hundred seconds. Amongst them, a good fraction of the SGRBs are followed by a kilonovae *e.g.* GRB 050724 [94], GRB 060614 [95], and GRB 080503 [96]. The fluence of the extended emission of some of these SGRBs is higher than the prompt emission [94]. It is also worth mentioning that the extended emission was not found in GW170817, suggesting either that NS mergers with masses similar to GW170817 do not produce extended emission or that it was produced in GW170817 but was significantly beamed away from the Earth [97]. These observations pose few important questions: Are their progenitors different from SGRBs without extended emission? What

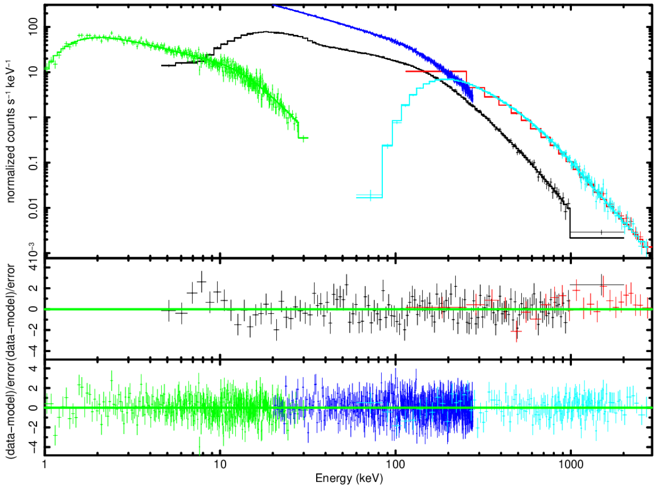

Fig. 4 Simulated spectrum of a typical GRB, assuming a Band function spectrum [92] with $\alpha = -1.0$, $\beta = -4.0$, $E_c = 300$ keV, and a $10 - 1000$ keV fluence of $\sim 1 \times 10^{-5}$ erg cm^{-2}. Background statistics are not considered in these simulations. The top panel shows the GRB spectra and the fitted model. In the Middle panel we have shown the residuals with GBM spectra. Black and Red colours correspond to single NaI and BGO detectors, respectively. The figure at the Bottom panel shows the residuals for *Daksha*. The green, blue and aqua colours show the spectra obtained using just one each of LEP, MEP and HEP. In practice, the effective are is much higher when adding the signals from multiple detector packages, but this example suffices to show the high sensitivity. The response files used for LEP and MEP assume an on-axis incidence, while for the HEP we have used a response file with a slightly off-axis angle of incidence. This approximation does not significantly affect the results.

is the energy source of long lasting emission if they arise from binary NS mergers?

It has been suggested that the extended emission can be powered by the spin-down luminosity of a remnant magnetar or the Blandford-Znajek process of a remnant Kerr black hole in NS mergers [18]. The detection of an extended emission associated with the GW from confirmed BNS merger event will shine light on this as well as the nature of GRB central object. *Daksha*, with its high sensitivity and wide bandpass, particularly extending down to soft X-rays, is ideally suited to investigate these aspects.

4.5 Time-resolved studies

The time resolved prompt emission studies are governed by two distinct patterns in the evolution of the peak energy E_p: *first* the spectral evolution from hard to soft energies. This can be explained by the matter dominant jet outflow first giving black body radiation from the collapsing material [98] and then emitting non thermal photons resulting from interaction of internal shocks interacting with optically thin region above the photosphere [99]. *Second*, the luminosity correlation with temperature [100] resulting in flux driven spectra taking into account the local magnetic-energy dissipation in a Poynting flux dominant outflow fueling the acceleration of the flow to a high bulk Lorentz factor. For typical GRB parameters, the dissipation takes place mainly above the photosphere, producing non-thermal radiation [101]. In order to understand the underlying emission mechanism and to reach to a unifying physical model, we need observations with fine time resolved prompt spectra as well as ample GRBs with soft energy detection.

Even for short GRBs, investigating temporal evolution is of great importance. The short GRB jet propagating inside the merger ejecta forms a cocoon, which eventually breaks out from the ejecta surface. The emission arising from the cocoon shock break-out is expected to be composed of an initial hard-spike followed by a soft-tail [102, 103]. The luminosity, duration, and spectral peak of the hard spike and soft tail depend on the ejecta structure as well as the jet properties such as the power, opening angle and time delay between the merger and jet launch. By modeling the emission properties with time resolved spectroscopy of the prompt phase, we will be able to obtain valuable information about the structure of merger ejecta and the jet formation in neutron star mergers. This in turn may allow us to constrain the neutron star equation of state (EOS) since the ejecta profile in the fast tail is sensitive to the EOS [104, 105]. *Daksha* with micro-second time resolution capabilities and broadband energy coverage (including the soft X-ray energies) is well suited to probe the temporal evolution of the prompt phase for long as well as short GRBs.

4.6 Polarization from GRBs

Polarization from GRB emission can be an important tool to probe the physics of emission mechanisms in GRBs, the geometry of the emission region, and the origin and nature of the magnetic field at the emission region [106–108]. Till date polarization has been detected in only a handful of sources [17, 109, 110]. There is significant debate in the literature regarding the source of the polarization e.g. synchrotron with ordered magnetic fields, synchrotron with random magnetic fields at shocks, and inverse Compton interactions [106, 109, 111, 112]. Different theoretical models predict varying degrees of maximum polarization, based on the magnetic field, geometry and the viewing angle [107, 109, 113]. If the polarization is due to synchrotron processes, as is often conjectured [114], then a high polarization fraction would imply ordered magnetic fields within the jet structure. A disordered magnetic field structure that many theories propose may arise at the forward shock [115] would lower the polarization. Contemporary work on GRB spectra indicate the prompt emission resulting from synchrotron radiation(non-thermal) [116, 117]. However, spectral modeling of photospheric emission(thermal) has also provided adequate fits to a subset of GRBs [118]. A combined study of the GRB spectrum and polarization will break the degeneracy between various such theoretical models.

Variation of the GRB polarization degree and the polarization angle has been observed in very few sources [110, 119–122]. Time-resolved polarization studies are challenging due to insufficient photon counts during a GRB outburst. However, such observations can be a valuable tool to understand the internal structure of the GRB jet and the nature of emission. Different theoretical models have put forth possible predictions of variation of the polarization angle, for example, the evolution of viewing angle cone resulting in observing different magnetic field geometries [113] or inherently patchy, non-axisymmetric emission due to internal fluid inhomogeneities [123]. The strength of the observed polarization fraction and nature of the variation will help distinguish between such models [e.g. as reported in 120, 122], which will provide valuable constraints on the nature of GRB outflow.

Daksha, with its pixellated CZT detectors with large collecting area will be able to measure polarization of hard X-rays in the prompt phase for GRBs having sufficient brightness. Figure 5 shows simulation results showing hard X-ray polarization measurement capabilities of *Daksha*. Our preliminary study finds that the MDP for Daksha will be 0.31 for a fluence of 10^{-4} erg cm^{-2}, and we expect to measure polarization for nearly 5 – 8 GRBs per year with a fluence of more than 10^{-4} erg cm^{-2}. In the lifetime of Daksha, it will obtain a homogeneous GRB polarization sample to constrain physical models of GRB prompt emission. The details of the polarization sensitivity of *Daksha* (including the measurement method) will be published in Bala et. al (in prep).

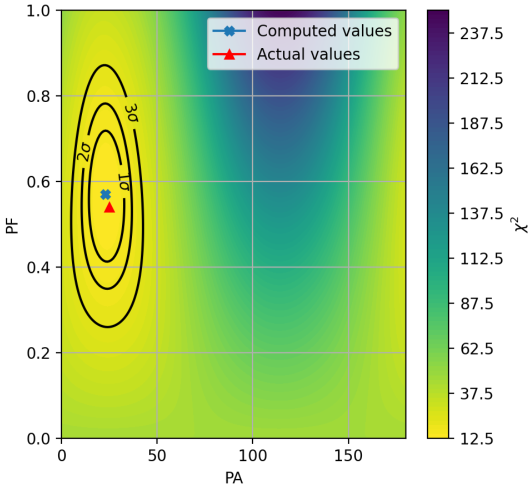

Fig. 5 The plot shows hard X-ray polarization measurement capability of *Daksha* using GRB 160821A as an example. GRB 160821A had a fluence of 1.32×10^{-4} erg cm^{-2} in the energy range 10 – 1000 keV (3.64×10^{-5} erg cm^{-2} in 20 – 200 keV). The red point shows the injected GRB with polarization angle (PA) = 25° and a polarization fraction (PF) of 0.54 while the blue point shows the recovered value of PA (=23°) and PF (=0.57). The recovered value lies well within 1-σ contour.

As an illustration, we consider the case of the polarized GRB 160821A. The GRB had a 10 – 1000 keV fluence of 1.32×10^{-4} erg cm^{-2}, and a duration $T_{90} = 43$ s. We model the GRB spectrum as a Band function with parameters $\alpha = -1.05$, $\beta = -2.3$, and $E_{\rm peak} = 941$ keV.

5 Additional science goals

As a sensitive all-sky monitor, *Daksha* data can be used to probe many other scientific questions. Here, we discuss some of the science cases.

5.1 Magnetar Bursts

Magnetars are young (age $\lesssim 10^4$ yrs), highly magnetized ($B_{\rm surf} \sim 10^{13-16}$ G) neutron stars, that are notorious for their wide variety of high-energy transient phenomena [see 124, for an observational and theoretical review]. These include outbursts which last for months to giant flares that have been known to emit 10^{46} erg in $\approx$100 ms [125]. With it's lower fluence threshold, wide energy range, and sky coverage *Daksha* will be a valuable tool for probing magnetar bursts and flares from the Milky Way magnetars as well as giant flares from magnetars in nearby galaxies ($d \lesssim 10^2$ Mpc). The increased volume probed by *Daksha* will allow for a better understanding of magnetar burst rates, luminosity distributions, and the birth-to-death cycle of magnetars.

For brighter bursts, *Daksha*'s polarization capabilities will allow for the measurement of linear polarization which is expected to occur due to the propagation of photons through extremely strong magnetic fields [$B \sim 10^{15}$ G, 126]. While other planned X-ray polarization missions aim to study the polarization of persistent emission from magnetars, *Daksha*'s polarization measurement capabilities over a near-all-sky field of view are required for polarization measurements of magnetar bursts.

5.2 Fast Radio Burst Counterparts

FRBs are recently discovered millisecond timescale radio transients that are detected from cosmological distances ($\sim$Gpc). The isotropic burst energies of FRBs (10^{38-42} ergs) are almost a trillion times higher than the brightest radio pulses observed from Galactic pulsars. Due to the short timescale and the luminosity of FRBs, neutron stars, especially magnetars [e.g. 127, 128] are leading candidates for their origins. Similarly, many FRB models expect prompt radio counterparts to be emitted with BNS and NSBH mergers [129–133]. From the large volumetric rates of FRBs, compared to those of BNS and NSBH mergers, it is clear that these would contribute to a small fraction of observed FRBs. To date, while the observational data is rapidly increasing, the evidence is heterogenous with a multiple theories [see e.g. 134, for a review] and plenty of open questions remain about the origins of FRBs [135, 136].

Most mechanisms expect that the radio emission of fast radio bursts is a small fraction of the total burst energy and prompt counterparts as well as afterglows are expected in different wavebands, including X-rays. Due to the extreme sensitivity of radio telescopes compared to X-ray and optical telescopes, it is expected that most models predict that typical FRBs will not have detectable high-energy counterparts. By significantly increasing the rate of X-ray and gamma-ray transients, *Daksha* will be able to help identify and constrain X-ray and gamma-ray counterparts of FRBs, a search that has yet been unsuccessful from existing missions, see e.g. [137–141].

On 2020 April 28, an energetic radio burst with a total isotropic radio emission of 10^{34} erg from the Galactic magnetar SGR 1935+2154 [142, 143] accompanying an X-ray burst with an energy of $\approx 10^{39}$ erg. The X-ray burst was delayed by 6 ms relative to the radio emission and was significantly harder ($E_{\rm peak} \sim 65$ keV) compared to typical magnetar bursts [144]. While the radio energy output of this burst was few orders of magnitude lower than that of typical FRBs, this burst was the brightest radio transient ever observed and partially bridges the energy gap between radio pulsars and FRBs. For a 10 ms burst, *Daksha* has a 5-σ fluence sensitivity of $7{\times}10^{-8}$ erg cm^{-2}. Given the scarcity of bright FRBs and the faintness of their corresponding high energy counterparts, *Daksha*'s broad sky-coverage and low fluence threshold will be able to detect or rule out high energy counterparts to FRBs detected by ground-based instruments such as CHIME [145], ASKAP [146], STARE2 [147] and upcoming telescopes such as BURSTT [148].

5.3 X-ray pulsars

The accretion powered X-ray pulsars are laboratories for study of various phenomena involving matter in strong magnetic fields. The accreting matter imparts or draws out angular momentum from the neutron star. Both the accretion torque and the X-ray beaming from the neutron star are dependent on the mass accretion rate and structure of the accretion column on the magnetic poles of the neutron star. For a neutron star with a supergiant companion star, the mass accretion from the wind causes these sources to show random variation in accretion torque. However, these sources occasionally show rapid spin-up phases, indicating a change in the mode of accretion from wind to a disk. Study of various pulsar characteristics like pulse shape, pulse fraction etc. at different accretion torque level measured with *Daksha* will lead to better understanding of the relative importance of the two accretion mechanisms in the persistent accretion powered X-ray pulsars. The neutron stars with Be-Star companions undergo large outbursts during which the neutron star shows large spin-up followed by slow spin-down during the quiescence. Measurement of the accretion torque as a function of the accretion power and the pulse profiles of X-ray pulsars will therefore be very useful in study of the accretion processes in high magnetic field neutron stars over a large range of mass accretion rate. Isolated X-ray pulsars and magnetars can also undergo discontinuous changes in their rotation rate (glitches and anti-glitches), some times accompanied by large scale pulse profile and emission mechanism changes.

As an all sky X-ray sensitive satellite, *Daksha* will be able to gather time-tagged photons from all sources in the sky. The absolute timing precision of *Daksha* of the time-tagging will be sub-ms. Since individual *Daksha* detectors lack directionality, photons from any specific source will be confused. However, by barycentering the arrival times and optimally combining photon counts from different detector facets of *Daksha*, we can search for periodic astrophysical signals in a frequency–frequency derivative–sky-position phase space. For known pulsars, we can use *Daksha* photons to continuously monitor the spin periods for variations with accretion rates, detect glitches, and refine their ephemeris. This monitoring can simultaneously cover all the X-ray bright pulsars in the sky, unlike the monitoring with radio telescopes. In addition to barycentering the data and combining the signals from different detectors, *Daksha* can also use Earth occultation (see Section 5.5) as a method to distinguish photons from bright sources near the Earth limb.

We calculated the expected source count rates for these sources with *Daksha* ME detectors based on the *NuSTAR* 20–50 keV spectra of several accretion powered pulsars. We created lightcurves for these pulsars based on the *NuSTAR* pulse profiles in the same energy band, scaled appropriately and a background rate of $\sim 7400\,\mathrm{cts\,s^{-1}}$ (for seven surfaces). We simulated observations of these pulsars with an integration time of 2.5 days with a duty cycle appropriate for the low-earth orbit of *Daksha*. A Lomb-Scargle periodogram search was used to determine the pulsed flux level required to detect the pulsation above a 3-σ and 5-σ threshold.

The simulations show that accretion powered pulsars with a flux level above $2.6\times10^{-10}(3.1\times10^{-10})\,\mathrm{ergs\,s^{-1}\,cm^{-2}}$ in the 20–50 keV band will be detected with *Daksha*-ME at 3-σ (5-σ) level in every 2.5 day interval. Figure 6 shows these limits in comparison with the pulsed flux measurements of GX 301–2 from *Fermi*-GBM. The detection threshold depends partly on the pulsed fraction and the pulse shape of each source. *Daksha*-ME will therefore be able to carry out continuous monitoring of the pulsar frequency and pulsed flux history of about 10 persistent X-ray pulsars. A large number of transient pulsars (about six transient pulsars every year) will also be monitored during their outbursts. About two new transient pulsars are expected to be discovered every year. For study of accretion powered X-ray pulsars, *Daksha*-ME is at par with *CGRO*-BATSE and *Fermi*-GBM which have been extremely useful for study of this type of sources in the last three decades.

5.4 Primordial black hole abundance

The nature of dark matter remains one of the biggest puzzles in cosmology today. Primordial black holes (PBHs) that formed very early in the history of the Universe have been suggested as possible candidates to make up a large fraction of dark matter [149, 150]. Cosmological observations including the cosmic microwave background, as well as various microlensing surveys carried out from both ground and space have ruled out a vast parameter range for the possible masses of such primordial black holes [see e.g., 151]. However,

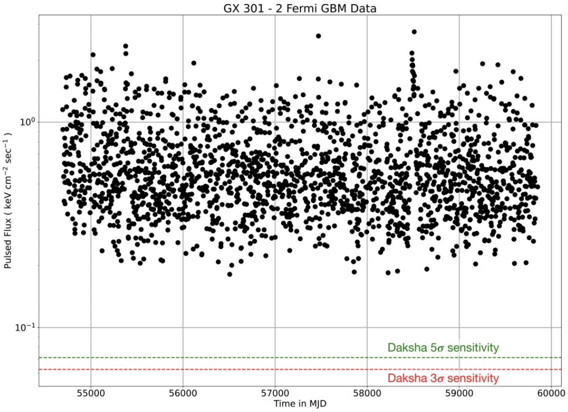

Fig. 6 Pulsed flux of GX 301–2 from *Fermi*-GBM observations (black dots) compared to the *Daksha*-ME detection thresholds (green: 5-σ, red: 3-σ)

there exists a window in the mass range $[10^{-11} - 10^{-16}]M_{\odot}$ where such PBHs remain unexplored thus far. Such PBHs could even make up the entirety of the dark matter, thus solving the dark matter puzzle without recourse to any new particle physics. Such mass scales cannot be explored with light in the optical wavelength range, as the Schwarzschild radii of such black holes are smaller than the wavelength of optical light [see e.g. 152]. Due to its wide wavelength coverage, *Daksha* will probe this mass range in its high energy band. The two *Daksha* satellites will enable a unique parallax microlensing experiment for the first time, where the same GRB can be observed with two different lines-of-sight [see e.g. 153]. The PBH will be at a different impact parameter compared to the GRB for the two different satellites, thus causing a difference in the measured flux of the GRB. A null detection of a difference in flux (i.e. no detection of lensed GRBs) can constrain the PBH abundance in the unexplored mass range. Assuming *Daksha* detects a sample of 10000 such GRBs, we can expect to constrain the fraction of dark matter locked in PBHs in the aforementioned mass range to $f_{\rm PBH} \leq 0.5$ at 95 percent confidence (Gawade et al., in preparation). Alternatively, a detection of a difference in the detected fluxes of the same GRB from the two satellites will open an exciting possibility of finding such tiny primordial black holes for the very first time. This experiment will require excellent cross-calibration between the detectors on board the twin *Daksha* satellites.

5.5 Earth Occultation Studies

The background for *Daksha* arises from the diffuse cosmic X-ray background, a relatively small contribution from electronic noise, and counts from bright point sources in the sky. The occultation of these bright sources by the Earth

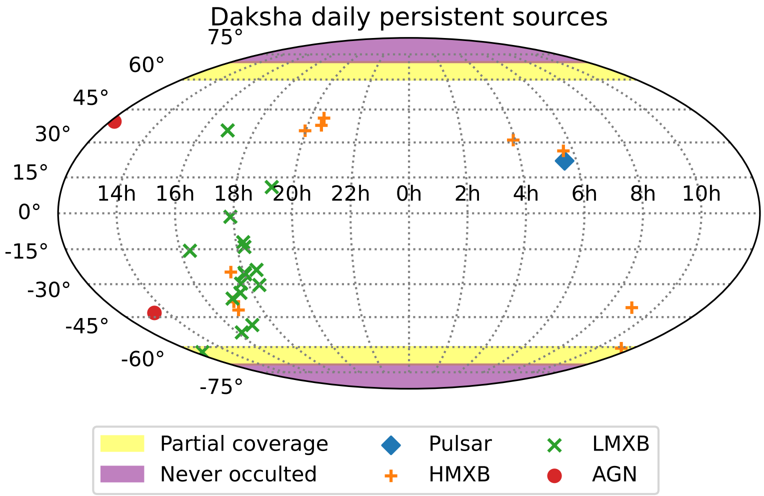

Fig. 7 Sources whose flux can be monitored daily with *Daksha* by the Earth Occultation technique. In addition to these persistent sources, bright transient sources like novae, X-ray binaries outbursts, etc can also be detected with this technique.

causes changes in the net count rate, which can be used to monitor the brightness of these sources [154]. We follow the method defined in Singhal et al.[155] to calculate the sensitivity of *Daksha* for such measurements. The instant of the occultation event (ingress or egress) is known from the coordinates of the source and the orbital position of the satellite. We measure the flux levels in 100 s pre– and post– event windows, and estimate the change in flux from the change in counts. We have to account for one subtlety in these calculations: source photons are incident on the projected area of the satellite, while the background rates are determined by the total physical area of the relevant surfaces. We do these calculations considering a nominal case with the median effective area (1310 cm^2) for the source and seven surfaces for the background. We calculate that for a single ingress or egress, the 3-σ sensitivity of *Daksha* is 0.048 ph cm^{-2} s^{-1} (186 mCrab) in the 20–200 keV band. Each satellite completes about 14 orbits per day, with two measurements per orbit. Combining data from both satellites, the daily averaged sensitivity is 0.0064 ph cm^{-2} s^{-1} (25 mCrab).

We used the *Swift*-BAT catalogue [156] to estimate the number of sources that can be detected every day by *Daksha*. Using the reported hard X-ray fluxes and power-law indices, we calculate that *Daksha* can provide daily flux measurements of 29 sources: two active galactic nuclei (Cen A, NGC 4151), the Crab Pulsar, ten High Mass X-ray Binaries, and sixteen Low Mass X-ray Binaries. As seen in Figure 7, most sources are along the galactic plane. Note that sources in the $\pm(60° - 70°)$ declination range are not occulted in every satellite orbit, owing to the 6° orbital inclination. Sources close to the poles are never occulted by the Earth for *Daksha*, and cannot be monitored by this method.

5.6 Novae

In addition to the study of persistent sources, the Earth occultation technique can also be used to detect bright transient sources like novae, outbursts of X-ray binaries, etc. As an illustration, we discuss the hard X-ray detectability of novae. Soft X-rays have been commonly detected in novae, but hard X-ray detections remain few in number — and the emission mechanisms are poorly understood [157, 158]. Theoretical models predict that the early flash may be as bright as 0.1 ph cm^{-2} s^{-1} in the 100–200 keV band, with emission fading rapidly to lower levels over the timescale of a day [159, and references therein]. However, some novae have been bright in hard X-rays: for instance, the 2006 outburst of recurrent nova RS Oph was detected by *Swift*/BAT [160], and the 2015 outburst of GK Per was detected by *Integral* [161]. Pointed hard X-ray observations of novae have led to more detections, with steep power-law spectral slopes: $\Gamma = -3.6$ for V5855 Sgr [162], -3.9 for V906 Car [163], and -3.3 for YZ Ret [164].

Predictions for hard X-ray fluxes of novae are often made by extrapolating the low-energy models [see for instance 160]. To estimate if RS Oph would be detectable by *Daksha*, we follow the approach of Page et. al. 2022 [165] by fitting the *Swift*-XRT data with an APEC model, and calculating the expected flux in the *Daksha* energy band (20–200 keV). We find that the source would have been detectable to *Daksha* from day 3–6 of the outburst.

A direct comparison with *Swift*-BAT lightcurves shows that *Daksha* can also detect X-ray novae like MAXI J1828−249 [166], GRS 1739–278 [167] and MAXI J1535−571 [168].

5.7 Terrestrial Gamma-ray Flashes

The Earth's atmosphere is populated by processes like thunderstorms, lightning, and related electrical phenomena which emit X-rays and gamma-rays. Despite their global occurrences, the underlying science of these critical electromagnetic phenomena is still poorly understood. One such phenomenon is Terrestrial gamma-ray flashes (TGFs) which were first detected in 1994 from space by Compton Gamma Ray Observatory [169]. TGFs are millisecond-duration sudden bursts of gamma-ray radiation having energies reaching as high as 100 MeV [170]. They are observed over thunderstorms and originate at around 20 km altitude [171]. On average 500 TGFs/day are expected to occur globally but not all get detected. Moreover, TGFs also produce energetic particles known as Terrestrial Electron Beams (TEBs) that are composed of mainly secondary electrons and positrons, which can be observed by spacecraft orbiting in the inner magnetosphere [172]. Their impact on the inner magnetosphere is unknown and warrants detailed investigation. The simultaneous conjugate studies with existing radiation belt missions like the Exploration of energization and Radiation in Geospace (ERG) /Arase [173] will help to decipher the linkage of the lower atmosphere and inner magnetosphere coupling.

High energy atmospheric physics is a new domain and evolving, the space-based continuous observations of gamma rays will assist in deciphering the unresolved problems of TGFs and TEBs. The microsecond time resolution and high sensitivity of *Daksha* in the hard X-ray band makes it a well-suited instrument for the study of TGFs. At an altitude of 650 km, *Daksha* can monitor a $\pm 25°$ band on the Earth's surface, corresponding to a footprint of $\sim$2700 km. Combined with the 6° inclination, the satellites will be able to detect activity in the latitude range from $-19°$ to $+19°$ in each orbit, reaching upto $\pm 31°$ in various parts of the Earth on successive passes.

Key instruments for the study of TGFs inclued *Fermi* and the Atmosphere-Space Interactions Monitor (*ASIM*) instrument on the International Space Station (ISS). We can compare the TGF capabilities of *Daksha* directly with the "Low Energy Detector" (LED) of the Modular X-ray and Gamma-ray Sensor (MXGS) on *ASIM*. The LED comprises of CZT detectors covering the energy range from 50 keV to 400 keV, with an effective area of 400 cm^2 at 100 keV and a time resolution of 1 μs [174]. *Daksha* has similar time resolution, and a much higher effective area: hence will be more sensitive to TGFs. The higher altitude of *Daksha* (650 km instead of 400 km) will also allow each *Daksha* satellite to view a much larger part of the Earth, while the near-equatorial orbit (as opposed to 55° orbit of the ISS) ensures that *Daksha* spends more time over areas with active thunderstorms, and avoids background magnetospheric particle fluxes as well as auroral X-ray emission which could have added to background noise. The orbital inclination is very important, and has been suggested to be the main reason why *ASIM* detects only about 260 TGFs/year while *Fermi* detects close to 800 TGFs/year [174, 175].The peak count rates reach tens of counts in 10 μs intervals, with only a fraction of events yielding over 100 counts. These rates are easily detectable in *Daksha*, where individual MEPs will have an average of 0.03 counts in 10 μs bins, and are designed to handle might higher peak count rates. TGFs are expected to have a few percent degrees of polarization [176] which varies with source altitude. *Daksha* will be able to put stringent observational constraints on the polarization of the brightest TGFs.

There are several ground-based facilities studying the atmosphere: electric field measurements, cosmic ray observations, mesosphere–stratosphere–troposphere (MST) radars, etc. Simultaneous data from *Daksha* and such facilities can give great insight in understanding association of TGFs with convective activities and their evolutions. A particular example of such a synergy will be joint studies with *Daksha*, the GRAPES-3 muon telescope [177], Equatorial secondary cosmic ray Observatory, Tirunelveli, India [178], and Indian MST radars [179, 180].

5.8 Solar Flares

Solar flares are sudden releases of energy in the solar atmosphere leading to emission across the entire electromagnetic spectrum, and often the release of energetic particles into the interplanetary medium. According to the standard flare model, the underlying mechanism powering the flares is magnetic reconnection that leads to acceleration of particles into non-thermal distributions and also heating of the plasma to temperatures often exceeding 10 MK [181]. While the standard flare model picture explains the observations in a broader context, several details such as the acceleration mechanism are still not well understood. As the accelerated electrons emit in hard X-rays by non-thermal bremsstrahlung, observations of the hard X-ray spectrum provide the most direct diagnostics of the non-thermal electron population [182]. By modeling the observed hard X-ray spectrum, the distribution of the non-thermal electron population as well as quantitative estimates of their total energy content can be obtained. Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI, 183) that observed the Sun in hard X-rays for 16 years until 2018 provided wealth of information on particle acceleration in solar flares with its broad band spectroscopic and imaging observations. RHESSI could observe non-thermal emission up to few tens of keV for flares down to GOES B-class intensities [184]; however, it was not possible to extend this to lower intensity flares.

Daksha, with its Sunward MEPs, will provide measurements of hard X-ray spectra of solar flares in 20–200 keV energy band. With 4 MEPs in the Sunward direction, Daksha will have about an order of magnitude larger effective area than that of RHESSI in this energy range. With the added advantage of simultaneous background measurements from other faces, Daksha is expected to have much better sensitivity than RHESSI for solar flare spectra. Simultaneous observations of flares by Daksha with instruments at other vantage points such as the Spectrometer/Telescope for Imaging X-rays (STIX, 185) on Solar Orbiter or various instruments of *Aditya-L1* [186] also provides the opportunity to probe hard X-ray directivity.

5.9 Earth-Sun interaction

X-ray fluorescence (XRF) emission is triggered by solar X-rays from planetary atmospheres along with a scattered continuum. The scattered X-ray spectrum from Earth's atmosphere in the soft X-ray regime is a representation of the incident solar spectrum from which solar coronal abundances have been derived by Katsuda et. al [187]. The LE detector package on Daksha would measure the scattered solar X-ray spectra over a dynamic range enabling solar coronal studies. The reduction in intensity by scattering especially during strong flares would be an advantage here where often sun pointing spectrometers reach a saturation. In addition, a mapping of the Ar elemental abundance in Earth's atmosphere would be possible from its X-ray fluorescence line.

6 Summary: the Impact of *Daksha*

Daksha has unprecedented coverage of the transient high energy sky. As discussed in Paper I, the overall "grasp" of the mission, defined as the product of effective area and sky coverage, is higher than any current or proposed missions. Thanks to this, *Daksha* will discover the highest number of high energy counterparts to gravitational wave sources. It will boost our understanding of GRBs with prompt soft X-ray spectroscopy, highly time-resolved spectroscopic studies, and polarization measurements.

In addition, *Daksha* covers a large number of secondary science cases. Compact object studies will benefit from continuous monitoring of accreting X-ray pulsars, detection and characterization of magnetar bursts, and the search for counterparts to FRBs. *Daksha* can monitor persistent sources and slower timescale transients like Novae to a sensitivity of 25 mCrab by the Earth Occultation Technique. The two identical satellites in the mission will allow us to probe primordial black hole abundance through microlensing. Closer in, *Daksha* will provide excellent data for the study the Sun, TGFs, and the atmospheric response to solar activity.

As mentioned in Paper I, *Daksha* was proposed in response to the Indian Space Research Organisation's Announcement of Opportunity (AO) for Astronomy missions in 2018. The proposal was shortlisted for further studies, and was awarded seed funding by the Space Science Program Office for demonstration of a proof-of-concept. The team has completed the construction and testing of a laboratory model of the Medium Energy detector Package, as required. *Daksha* builds heavily on the legacy of various Indian space science missions, giving a high technology readiness level to all subsystems. The mission will be reviewed for full approval, after which we target a development timeline of three years to launch.

Acknowledgments

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Software

Numpy [188], Matplotlib [189], Astropy [190, 191, http://www.astropy.org], HealPIX [192], Healpy (https://healpy.readthedocs.org/), Ephem (https://

pypi.python.org/pypi/pyephem/), WebPlot Digitizer https://automeris.io/WebPlotDigitizer, GEANT4 [193, https://geant4.web.cern.ch/]

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