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 > 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 (LIGO Scientific Collaboration et al. 2017; Abbott et al. 2017a) 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 (Watson et al. 2019; Kasliwal et al. 2017a) and independent measurements of the neutron star equation of state (De et al. 2018).

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 (Zhang et al. 2018). 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 ≥ 100 Mpc. Despite extensive searches, no EM counterpart were found (see for instance Hosseinzadeh et al. 2019; Coughlin et al. 2019). 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 (Schönfelder et al. 1984; Band et al. 1993a), BeppoSAX (Boella et al. 1997), Swift (Gehrels et al. 2004; Barthelmy et al. 2005) and Fermi (Meegan et al. 2009) leading the exploration of GRBs, magnetar flares, and X-ray binary outbursts. More recently, instruments such as AstroSat CZTI (Bhalerao et al. 2017), POLAR (Produit et al. 2005), and IKAROS-GAP (Yonetoku et al. 2011a) 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 (Metzger et al. 2008; Kumar & Zhang 2015).

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 (LIGO Scientific Collaboration et al. 2015), adVirgo (Acernese et al. 2015), KAGRA (KAGRA Collaboration et al. 2020), and LIGO-India (Iyer et al. 2011; Saleem et al. 2022). 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 (Bellm...
Rubin Observatory (LSST Science Collaboration et al. 2009), Square Kilometer Array (Dewdney et al. 2009), uGMRT (Gupta et al. 2017), LOFAR (van Haarlem et al. 2013), ASKAP (Johnston et al. 2007), and IceCube (Aartsen et al. 2017). 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 1–25 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.

The workhorse of Daksha are the ME detectors, which provide nearly uniform all-sky coverage with a median effective area of \(\sim 1300 \text{ cm}^2\) (Figure 2), and a 5-\(\sigma\) sensitivity of \(4 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}\) for 1-second bursts. Bursts with fluence of about \(1 \times 10^{-7} \text{ erg cm}^{-2}\) 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 (Abbott et al. 2017a; LIGO Scientific Collaboration et al. 2017). The high energy detection spurred broadband follow-up observations leading to the discovery of a kilonova (Kilpatrick et al. 2017), and eventually proving that the merger produced a successful structured jet (Mooley et al. 2018a,b; Troja et al. 2018). 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 (Goldstein et al. 2017), establishing that such mergers indeed are the sites of r-process nucleosynthesis (Kasen et al. 2017; Kashiwal et al. 2017b), providing an independent measurement of the Hubble constant (Abbott et al. 2017c), and a measurement of the equation of state of ultra-dense matter (Abbott et al. 2018a, 2019).

GRB 170817 was peculiar in many ways. It was detected further off axis than typical GRBs (Mooley et al. 2018c,b; Beniamini & Nakar 2019). The prompt emission had soft spectral components which could not be adequately characterized or explained (Goldstein et al. 2017). 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 (Zhang et al. 2018). Had this event even been 30% fainter for instance, it would have been missed by several EM missions (Saleem et al. 2020). 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 (Hosseinzadeh et al. 2019; Coughlin et al. 2020). Besides sensitivity, GW170817 also underscored the importance of continuous all-sky coverage: sensitive missions like Swift (Evans et al. 2017) and AstrotSat (Kashiwal et al. 2017a) 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 (Bégué et al. 2017) 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 SGRB distribution as well as into the physics of SGRB jet structure, energetics (Hotokezaka et al. 2018; Beniamini et al. 2019).

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 (Abbott et al. 2018b). Additional advanced detectors such as the Japanese detector KAGRA (Aso et al. 2013) and the LIGO-India (Saleem et al. 2022) will make the network uniformly sensitive over the sky, with the localization capability up to ten square degrees (Mills et al. 2018; Abbott et al. 2020). A growing number of BNS sources will be detected within a few hundred Mpc (Burns et al. 2019; Petrov et al. 2022). To maximize the science returns from these detections, we need new higher sensitivity instruments with all-sky coverage (Abbott et al. 2017a; National Academies of Sciences Engineering and Medicine 2021).

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 (§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 §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 §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 (§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 (Gottlieb et al. 2018a; Beloborodov et al. 2020a). 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 \( \sim 2 \times 10^{11} \) cm, a maximum ejecta velocity of \( \sim 0.7c \) (Gottlieb et al. 2018a). 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 (Nakar & Sari 2012). 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 neutron star equation of state (EOS) since the ejecta profile in the fast tail is sensitive to the EOS (Hotokezaka et al. 2018a; Radice et al. 2018a).

3.3. Rates

The rate of joint EMGW detectors 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 Kagura. Following Petrov et al. (2022), we assume that the detectors have a duty cycle of 70%, and an event is considered to be detectable in gravitational waves if the network signal-to-noise ratio (SNR) is \( > 8 \). We take \( \mathcal{R} = 320 \text{ Gpc}^{-3}\text{yr}^{-1} \) from Abbott et al. (2021a).

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 (Goldstein et al. 2017). 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 Ioka & Nakamura (2019), where the jet energy \( E_\gamma \) and the Lorentz factor \( \Gamma \) are given by,

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

\[
\Gamma(\theta) = \Gamma_{\text{max}}/(1 + (\theta/\theta_0)^\lambda) \tag{2}
\]

where \( \theta_0 = 0.059 \) rad, \( \Gamma_{\text{max}} = 2000 \) and \( \eta_\gamma = 0.1 \). The event duration was assumed to be 0.3 s for all the events, the typical sGRB duration (Kouveliotou et al. 1993). Source energies \( (E_0) \) are drawn from the Wanderman & Piran (2015a) luminosity function. 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 (Beniamini & Nakar 2019).

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 Abbott et al. 2021b, 2022). 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 (Bloom et al. 2002; Hjorth et al. 2003; Hjorth & Bloom 2012), 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 of GW170817 confirmed that at least a class of short GRBs are produced by binary neutron star (BNS) mergers (Abbott et al. 2017d).

A typical GRB emission consists of two main parts: the prompt phase which consists of the immediate \( \gamma-\)

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\(^1\) This implies that there is no bright jet even for face-on observers.
rays produced close 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 (Greiner, J. et al. 2009; Gendre, B. & Boër, M. 2005; Schady 2015). 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 (Kumar & Zhang 2015). The composition of GRB jets, the radiative processes giving rise to the prompt γ-rays are some of the open ended questions (Kumar & Zhang 2015). Both in terms of spectral properties and physical mechanisms, prompt emissions are still comparatively poorly explored (Zhang 2011) as opposed to the afterglow phase due to the transient nature of the event and lack of observations in the soft X-ray band (Gehrels & Mészáros 2012; Oganesyan, G. et al. 2018). 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. 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 \( (\Delta t) \) 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 (2010), whereas, a model of lognormal distribution is adopted for the time delay from Wanderman & Piran (2015b). The various parameters defining \( R_{GRB}(z) \), \( \phi(L) \) and \( \Delta t \) 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.

![Figure 3. The cumulative plot showing the long and short GRB detection rate (per year) the by Daksha and Swift as a function of redshift.](image)

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 \( \Omega T/(4\pi) = 87\% \) (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 (Band et al. 1993a), known as Band model or Band function. The typical GRB spectra in \( \nu E_{\nu} \) form, shows a peak around energy of \( \sim 100 \) keV, characterized by the peak energy \( E_{\nu} \) of the Band function. The spectra below and above \( E_{\nu} \) are characterized by two spectral indices \( \alpha \) and \( \beta \) of the Band function. It has been observed that the peak energy is correlated to the isotropic equivalent energy of GRBs (Amati et al. 2002; Amati

\(^{2}\) Note \( \Delta t \) is estimated for the short GRB distribution only.
Further, it has been found that the isotropic equivalent energy of the prompt emission is correlated with the Lorentz factor of the outflow (Liang et al. 2010; Ghirlanda et al. 2012), 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 (Derishev et al. 2001; Daigne et al. 2011). 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 $\nu_c$ or the self-absorption frequency $\nu_{sa}$ being comparable to the characteristic synchrotron frequency $\nu_m$ (Daigne et al. 2011; Beniamini & Piran 2013). 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 $\alpha = -2/3$) (Nakar et al. 2009). 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 (Uhm & Zhang 2014). Moreover, synchrotron spectra can have photon indices much harder than $-1.5$ if the pitch angles of the emitting electrons are distributed anisotropically (Medvedev 2006). It is then extremely important to explore whether these proposed scenarios represent a viable solution and are supported by observational evidence.

Oganesyan et al. (2018) 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 of GRBs. Figure 4 shows the simulated spectra of a GRBs with 10–1000 keV fluence of $1 \times 10^{-5}$ 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 (Norris et al. 2010), GRB 060614 (Bostanci et al. 2012), and GRB 080503 (Perley et al. 2009). The fluence of the extended emission of some of these SGRBs is higher than the prompt emission (Norris et al. 2010). 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 (Abbott et al. 2017b). These observations pose few important questions: Are their progenitors different from SGRBs without extended emission? What 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 (Metzger et al. 2008). 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 (Shemi & Piran 1990) and then emitting non thermal photons resulting from interaction of internal shocks interacting with optically thin region above the photosphere (Daigne & Mochkovitch 1998). Second, the luminosity correlation with temperature (Golenetskii et al. 1983) 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 (McKinney & Uzdensky 2011). 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 (Gottlieb et al. 2018b; Beloborodov et al. 2020b). 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 (Hotokezaka et al. 2018b; Radice et al. 2018b). 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 (Covino & Gotz 2016; Lazzati et al. 2004; Waxman 2003). Till date polarization has been detected in only a handful of sources (Gill et al. 2020; Chattopadhyay et al. 2022; Yonetoku et al. 2011a). 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 (Beloborodov 2011; Toma et al. 2009; Covino & Gotz 2016; Gill et al. 2020). Different theoretical models predict varying degrees of maximum polarization, based on the magnetic field, geometry and the viewing angle (Ghisellini & Lazzati 1999; Lazzati et al. 2004; Gill et al. 2020). If the polarization is due to synchrotron processes, as is often conjectured (Burgess et al. 2020), 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 (Medvedev & Loeb 1999) would lower the polarization. Contemporary work on GRB spectra indicate the prompt emission resulting from synchrotron radiation(non-thermal) (Burgess et al. 2019; Troja et al. 2017). However, spectral modeling of photospheric emission(thermal) has also provided adequate fits to a subset of GRBs (Vianello et al. 2018). 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 (Götz et al. 2009; Yonetoku et al. 2011b; Zhang et al. 2019; Sharma et al. 2019; Chattopadhyay et al. 2022). 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 (Ghisellini & Lazzati 1999) or inherently patchy, non-axisymmetric emission due to internal fluid inhomogeneities (Lazzati & Begelman 2009). The strength of the observed polarization fraction and nature of the variation will help distinguish between such models (e.g. as reported in Yonetoku et al. 2011b; Sharma et al. 2019), 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).

As an illustration, we consider the case of the polarized GRB 160821A. The GRB had a 10 – 1000 keV fluence of $1.32 \times 10^{-4}$ 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 $E_{\text{peak}} = 941$ 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 ($B_{\text{surf}} \sim 10^{13-16}$ G) neutron stars, that are notorious for their wide variety of high-energy transient phenomena (see Kaspi & Beloborodov 2017, 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 (Hurley et al. 2005). 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, Taverna & Turolla 2017). 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. Metzger et al. 2019; Lyutikov & Popov 2020) are leading candidates for their origins. Similarly, many FRB models expect prompt radio counterparts to be emitted with BNS and NSBH mergers (Pshirkov & Postnov 2010; Totani 2013; Mingarelli et al. 2015; Paschalidis & Ruiz 2019; Rowlinson & Anderson 2019). From the large volumetric rates

![Figure 5. The plot shows hard X-ray polarization measurement capability of Daksha using GRB 160821A as an example. GRB 160821A had a fluence of $1.32 \times 10^{-4}$ erg cm$^{-2}$ in the energy range 10 – 1000 keV ($3.64 \times 10^{-5}$ 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.](image-url)
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. Platts et al. 2019, for a review) and plenty of open questions remain about the origins of FRBs (Petroff et al. 2019, 2022).

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. Cunningham et al. (2019); Anumarlapudi et al. (2020); Guidorzi et al. (2020); Curtin et al. (2022); Principe et al. (2022).

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 (CHIME/FRB Collaboration et al. 2020; Bochenek et al. 2020b) accompanying an X-ray burst with an energy of $10^{39}$ erg. The X-ray burst was delayed by 6 ms relative to the radio emission and was significantly harder ($E_{\text{peak}} \sim 65$ keV) compared to typical magnetar bursts (Mereghetti et al. 2020). 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-$\sigma$ 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 (CHIME/FRB Collaboration et al. 2018), ASKAP (Bannister et al. 2017), STARE2 (Bochenek et al. 2020a) and upcoming telescopes such as BURSTT (Lin et al. 2022).

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 $\sim 7400$ 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- and 5-σ threshold.

The simulations show that accretion powered pulsars with a flux level above $2.6 \times 10^{-10} (3.1 \times 10^{-10})$ erg 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.

![Figure 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)](image)

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 (Zel’dovich & Novikov 1967; Hawking 1971). 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., Carr & Kühnel 2020). However, 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. Niikura et al. 2019). 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. Jung & Kim 2020). 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 $f_{PBH} \leq 0.5$ 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 causes changes in the net count rate, which can be used to monitor the brightness of these sources (Harmon et al. 2002). We follow the method defined in Singhal et al. (2021) 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 sur-
faces. 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-$\sigma$ 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 (Oh et al. 2018) 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 ±(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 (Senziani et al. 2008a; Gordon et al. 2021). 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 (Senziani et al. 2008b, 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 (Bode et al. 2006), and the 2015 outburst of GK Per was detected by Integral (Tuerler et al. 2015). Pointed hard X-ray observations of novae have led to more detections, with steep power-law spectral slopes: $\Gamma = -3.6$ for V5855 Sgr (Nelson et al. 2019), −3.9 for V906 Car (Sokolovsky et al. 2020), and −3.3 for YZ Ret (Sokolovsky et al. 2022).

Predictions for hard X-ray fluxes of novae are often made by extrapolating the low-energy models (see for instance Bode et al. 2006). To estimate if RS Oph would be detectable by Daksha, we follow the approach of Page et al. (2022) 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 (Greene et al. 2016), GRS 1739–278 (Mereminskiy et al. 2017) and MAXI J1535–571 (Mereminskiy et al. 2018).

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 (Fishman et al. 1994). TGFs are millisecond-duration sudden bursts of gamma-ray radiation having energies reaching as high as 100 MeV (Tavani et al. 2011). They are observed over thunderstorms and originate at around 20 km altitude (Carlson et al. 2007). 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 (Dwyer et al. 2012). 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 (Miyoshi et al. 2018) will help

Figure 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.
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 $\pm 25^\circ$ band on the Earth’s surface, corresponding to a footprint of $\sim 2700$ km. Combined with the $6^\circ$ inclination, the satellites will be able to detect activity in the latitude range from $-19^\circ$ to $+19^\circ$ in each orbit, reaching upto $\pm 31^\circ$ in various parts of the Earth on successive passes.

Key instruments for the study of TGFs included *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 $\mu$s (Ostgaard et al. 2019). *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 $55^\circ$ 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 (Robert et al. 2018; Ostgaard et al. 2019). The peak count rates reach tens of counts in 10 $\mu$s 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 $\mu$s bins, and are designed to handle might higher peak count rates. TGFs are expected to have a few percent degrees of polarization (Bagheri et al. 2019) 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 (Hariharan et al. 2019), Equatorial secondary cosmic ray Observatory, Tirunelveli, India (Vichare et al. 2018), and Indian MST radars (Uma & Rao 2009; Subrahmanyan & Kumar 2022).

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 (Benz 2017). 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 (Krucker et al. 2008). 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, Lin et al. 2002) 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 (Hannah et al. 2008); 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, Krucker et al. 2020) on Solar Orbiter or various instruments of *Aditya-L1* (Seetha &
Megala 2017) 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. (2020). 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.

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