PROCEEDINGS OF SCIENCE

The Scientific Performance of the The Moon Burst Energetics All-sky Monitor (MoonBEAM)

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MoonBEAM is a SmallSat concept placed in cislunar orbit developed to study the progenitors and multimessenger/multiwavelength signals of transient relativistic jets and outflows and determine the conditions that lead to the launching of a transient relativistic jet. The advantage of *MoonBEAM* is the instantaneous all-sky coverage due to its orbit, which maximizes the gamma-ray transient observations and provides upperlimits for non-detections. Earth blockage and detector downtime from the high particle activity in the South Atlantic Anomaly region prevent gamma-ray observatories in low Earth orbit from surveying the entire sky at a given time. In addition, the long baseline provided from a cislunar orbit allows *MoonBEAM* to constrain the localization annulus when combined with a gamma-ray instrument in low Earth orbit utilizing the timing triangulation technique. We present the scientific performance of *MoonBEAM* including the expected effective area, localization ability and duty cycle. *MoonBEAM* provides many advantages to the gamma-ray and gravitational-wave follow up community by reducing the search region needed to identify the afterglow and kilanova emission. In addition, the all-sky coverage will provide insight into the conditions that lead to a successful relativistic jet, instead of a shock breakout event, or a completely failed jet in the case of core collapse supernovae.

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1. *MoonBEAM* Overview

The need for more gamma-ray instruments in orbit is critical for multimessenger and multiwavelength astronomy. As the larger gamma-ray instruments currently in orbit are aging and with no replacement on the horizon, many missions concepts have turned to smaller form factors such as CubeSats and SmallSats.

Most gamma-ray instruments are placed on satellites in Low Earth Orbit (LEO) in order to detect gamma rays above the Earth's atmosphere. However, satellites in LEO go through an area of high particle activity called the South Atlantic Anomaly (SAA), which requires detectors to be turned off to avoid negative effects, reducing the instruments duty cycle. The Earth also blocks 3̃0% of the field-of-view (FoV) for instruments in LEO, therefore if a gamma-ray transient were to occur behind the Earth the instrument would not be able to detect it. Furthermore, scattering off the Earth's atmosphere causes high background radiation and possible confusion of the gamma-ray transient's true location.

To solve the issues with instruments in LEO we present the Moon Burst Energetics All-sky Monitor (*MoonBEAM*) concept [9]. *MoonBEAM* is a sensitive gamma-ray mission with instantaneous all-sky gamma-ray field of view capabilities. *MoonBEAM* will be placed in a cis-lunar orbit allowing it to have a high-duty cycle (>98%), little Earth blockage and relatively stable background. *MoonBEAM* will be a nominal 2.5-year gamma-ray mission, with the possibility of extension, and the goal to observe gamma-ray transients from various progenitors (i.e. binary compact mergers, core collapse supernovae, and magnetar giant flares) and enable very high energy gamma-ray and optical follow up campaigns. The *MoonBEAM* baseline mission will contain 6 scintillating detectors strategically placed on the spacecraft to provide an instantaneous all-sky field-of-view, unocculted by the Earth. Using a detector design of two materials, sodium iodide

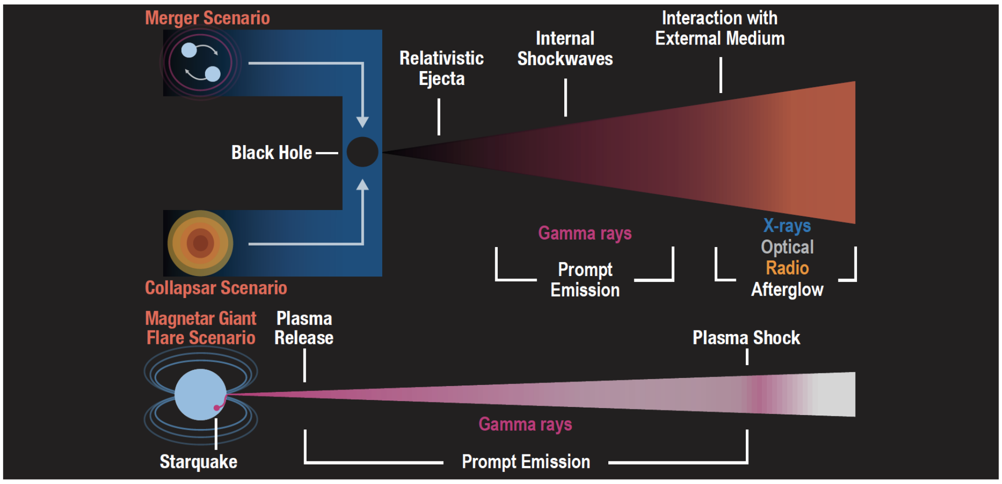

Figure 1: Schematic of how a central engine that launches a relativistic outflow can be formed from three known progenitors, mergers of compact objects, collapsars, and magnetar giant flares. The prompt gamma rays probe the launch and emission mechanisms and provide the first notice that a relativistic transient has occurred. This initial notice allows for follow-up observations that cover the full EM spectrum providing complete picture of the process.

NaI(Tl) and cesium iodide CsI(NaI), *MoonBEAM* will be sensitive to an energy range of 10–5,000 keV. The detector design utilizes a phoswhich configuration allowing for pulse shape discrimination (PSD) to distinguish in which scintillator a signal originated. The CsI(Na) component of the detector increases the energy range and effective area when compared to only NaI detectors. The detectors can also be used to localize a gamma-ray event with PSD to ignore (veto) any signals from the CsI(Na), significantly improving localization [18].

2. Science Goals

The science goals of *MoonBEAM* are to explore the behavior of matter and energy under extreme conditions by observing relativistic astrophysical explosions. Progenitors of these transient bursts of emission have been confirmed to be the merger of two compact objects (neutron star or black-hole), a collapsar (type of core collapse supernova), or a giant flare generated by a starquake on a magnetar (a neutron star with extremely powerful, large-scale magnetic field). Relativistic transients produce emissions across the electromagnetic spectrum (EM) as well as multi-messenger signals such as photons, gravitational waves (GWs), neutrinos, and cosmic rays. Figure 1 shows a schematic of these types of progenitors and how they produce not only prompt gamma-ray emission but long-lived multi-wavelength emission, and multi-messenger signals through relativistic jets and ejecta.

The science objectives of *MoonBEAM* are

1. Characterize the progenitors of gamma-ray bursts (GRBs) and their multi-messenger and multi-wavelength signals.
2. Identify conditions necessary to launch a transient astrophysical jet.
3. Determine the origins of the observed high-energy emission within the relativistic outflow.

To achieve these objectives, *MoonBEAM* aims to determine the percentage of binary neutron star (BNS) mergers that produce jets and the resulting jet width, assuming a Gaussian-shaped jet. *MoonBEAM* will also investigate the the percent of neutron star-black hole (NSBH) mergers that produce relativistic jets. Similarly, *MoonBEAM* will examine the percentage of Core Collapse Supernovae (CCSNe) that produce jets and the percentage of those that produce a choked or failed jet. *MoonBEAM* will also determine if magnetars can produce multiple magnetar giant flares (MGFs)[14]. Furthermore, *MoonBEAM* will enable optical follow-up of at least 300 GRBs and at least 10 very-high-energy (VHE) observations of GRBs within a redshift of 0.5 over its 2.5 year lifetime, based on GRB source rates from [17] and [8].

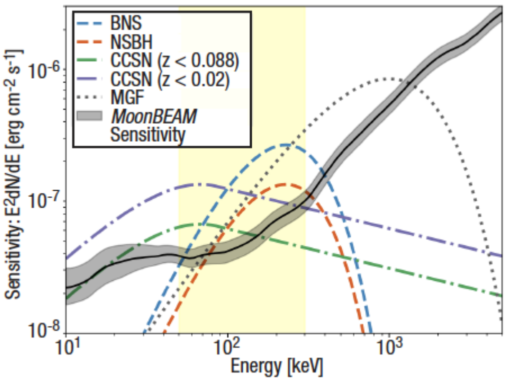

Figure 2: The projected 4.5 σ limiting. The sky-averaged sensitivity is the solid black line, and the gray band represents 99% of the variability of the sensitivity on the sky. The dashed lines represent the candidate spectra and fluxes for each of the various sources using the baseline mission requirements in order to set sensitive upper limits. The yellow shaded region is the energy range (50–300 keV) over which the minimum flux sensitivity requirement is set.

In the era of multimessenger astronomy, simultaneous broadband observations are vital for constructing a comprehensive picture of relativistic transients and the outflows they produce. Using joint multiwavelength and multimessenger observations to study the central engines that power these explosions is crucial to providing insights into the composition of relativistic outflows, and set strict constraints on the timescales for jet formation and propagation. *MoonBEAM* provides the essential continuous all-sky gamma-ray observations that were identified as a critical part of the Astro2020 Decadal Survey need for the next decade in transient and multimessenger astronomy [12], by reporting any prompt emission of a relativistic transient, and by providing rapid alerts to the astronomical community for contemporaneous and follow-up observations.

3. Science Implementation

The *MoonBEAM* science goals encompass a large distance and luminosity range. Observations of emissions from the various progenitors span over eight orders of magnitude in luminosity and a distance ranging from nearby galaxies to to the deaths of first-generation stars in the early universe. The ability to observe this dynamic range is critical to the science objectives.

The limiting flux was determined for the gamma-ray transient progenitor types to provide context for *MoonBEAM*'s sensitivity. The different progenitors have a large range of spectral variation between, and also within themselves, therefore the 50–300 keV energy range was appropriate to determine the limiting flux of these sources. For each of the scenarios in Figure 1, a candidate spectrum is used to calculate the limiting flux in the energy range 50–300 keV. The spectrum from GRB 170817A [6], the only confirmed GRB from a BNS merger, was used for the Merger Scenario. The spectrum from GRB 980425 [5], confirmed to be associated with a nearby CCSN, was used for the CCSNe Scenario. The spectrum of GRB 200415A [15], a bright extragalactic MGF from the Sculptor Galaxy, was used as a candidate spectrum for the MGF Scenario. Figure 2 shows these spectra in comparison to the projected performance of the *MoonBEAM* mission. The figure illustrates that 50–300 keV is the optimal energy range over which to detect the various progenitors. *MoonBEAM* will place sensitive limits on the flux of gamma-ray transient events in the case it does not detect the event but another instrument does.

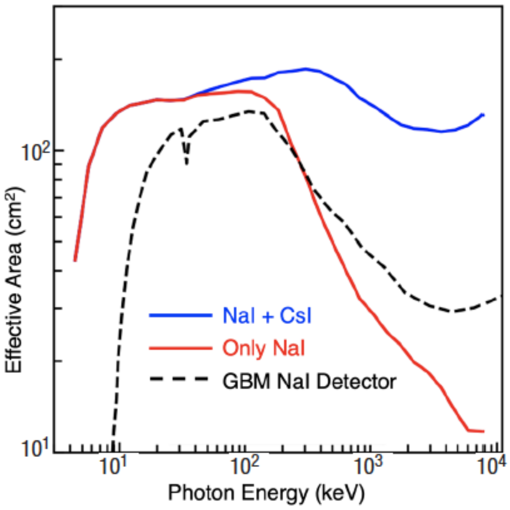

Figure 3: The MoonBEAM effective area as a function of photon energy for a single phoswich detector using both NaI and CsI materials (blue) is compared to using the phoswhich veto option of only the NaI material (red). A single Fermi-GBM NaI Detector is show in the dashed black line for reference.

The Medium-Energy Gamma-ray Astronomy Library [19], which uses Geometry and Data Tracking (Geant4) [1], was used to simulate gamma-ray interactions in a model of the *MoonBEAM* spacecraft. These simulations, incorporating all the major elements of the spacecraft, are used to determine various attributes of the science performance of the instrument, such as detector's effective area as a function of energy and direction, the sensitivity to GRBs, the intrinsic localization capability, and the response matrices. The simulations also provide the ability to examine the effectiveness of the phoswich veto mode and its impact on reducing the background rate and improving *MoonBEAM*'s localization of gamma-ray transients.

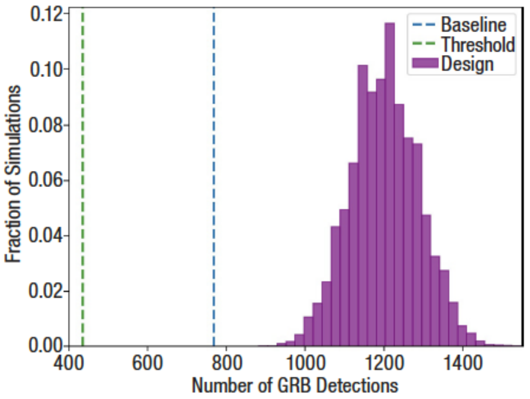

Figure 4: The predicted distribution of detected GRBs for the *MoonBEAM* mission timeframe. The baseline science requirement is the blue dashed line and threshold science requirement is green dashed line.

The on-axis effective area of one detector across the *MoonBEAM* energy band is shown in Figure 3 with a comparison to the phoswhich veto mode (Only NaI). The peak energy range of GRBs is between 50–300 keV [16], therefore an instrument must have sensitivity over that range to successfully detect GRBs. For the initial simulations, monoenergetic beams of gamma rays from 5 to 5,000 keV were used to determine the effective area across the sky. The average effective area at 300 keV is 645 cm^2 with minor fluctuations across the sky. The phoswich veto reduces the background incident on the rear of the detectors in this energy range and increases the angular dependence of the response for localization, justifying the phoswich design for localization.

MoonBEAM is sensitive to a broad energy range (10–5,000 keV) of photons and provides an energy resolution better than 12% at 662 keV. Using 10 years of GRB detections reported by the Fermi Gamma-Ray Burst Monitor (GBM) [16], we predicted the detection distribution of the *MoonBEAM* instrument by coupling its detection criteria and expected background rates. This GRB detection distribution is presented in Figure 4 for a time frame of 2.5 years of science operations. If *MoonBEAM* does not detect a GRB observed by another instrument, such as mergers seen in gravitational waves or supernovae detected in optical wavelengths, it will provide unprecedented sensitive gamma-ray upper limits. Figure 5 shows the limiting flux sensitivity of *MoonBEAM* across the entire sky. *MoonBEAM* provides a sensitivity improvement over current missions in LEO due to its combined advantages of cislunar orbit and instrument design.

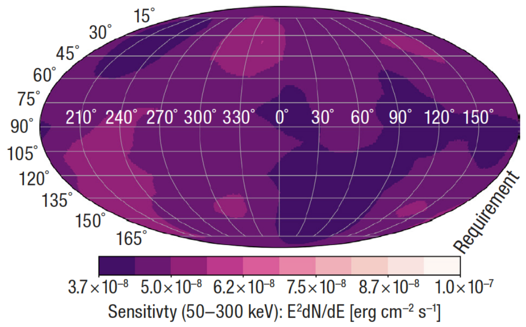

Figure 5: MoonBEAM's sensitivity across the sky. The sensitivity requirement is at the right most position in the scale. MoonBEAM is at least 2 times more sensitive at any point in the sky than this requirement.

The predicted *MoonBEAM* detection fraction of short GRBs detected as a function of 64-ms photon flux over 50–300 keV (the peak GRB energy range) was for both on-board and on-ground algorithms, shown in Figure 6. As expected, increasingly bright, short GRBs are detected at higher fractions. The figure compares the detection fraction curve for Fermi GBM, calculated in the same manner except with the observed Fermi GBM background rate, to *MoonBEAM* and clearly show that *MoonBEAM* is more sensitive to short GRBs than Fermi GBM. This is due to the lower background and increased detector size. For long GRBs the detection fraction was also calculated and is on par with Fermi GBM's performance. *MoonBEAM*'s performance is overall better due to the stability of the background and longer possible integration times.

For gamma-ray transients, it is essential to provide a localization for every GRB detected to enable multiwavelength/multimessenger follow-up. The localization informs telescopes where on the sky to observe to find a coincident counterpart [2, 4, 11] and provides information on whether two independent observations of a transient signal are associated. If a coincident counterpart is detected, the localization can be used to improve the localization even further. In order to localize GRBs, *MoonBEAM* uses a technique [3, 7] employed by Fermi GBM that generates count rate "templates" on a grid on the sky, assuming a particular GRB spectrum, for each of the detectors. These templates encode the expected relative count rates between each detector as a function of arrival direction and the observed count rates are compared to the templates at each point on the sky grid to compute a probability map.

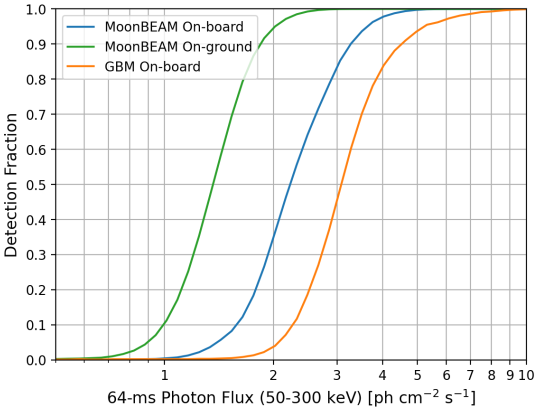

Figure 6: *MoonBEAM*'s threshold detection fraction of short GRBs as a function of photon flux. The black filled circle is the expected performance. For comparison, the corresponding detection fraction curve is shown for Fermi GBM.

We examined the *MoonBEAM* localization capability by simulating random GRBs sampled from the 10-year Fermi GBM spectral catalog [13]. Each randomly selected GRB is then assumed to arrive from a random direction, for which the *MoonBEAM* responses are generated to convert from photons to observed counts in the detectors. Following the same procedure, the localization capability of the phoswich mode was evaluated by using detector responses made from accepting photons that interact only in the NaI(Tl) (i.e., the CsI(Na) is used as a veto). Fifty percent of the ensemble of GRBs are located with a 1σ statistical error of 4.5°. A conservative systematic uncertainty of 3° is estimated from Fermi GBM [3, 7] and increases the total estimated localization uncertainty to 5.4°, which is comparable to Fermi GBM.

MoonBEAM will join the Interplanetary Gamma-Ray Burst Timing Network[1] (IPN) which combines the data from instruments both in and outside of LEO to achieve an improved localization though a timing triangulation method for any high-energy transients [10]. The current IPN consists of eleven missions, three of which are at interplanetary distances (Konus GRB instrument on Wind; Mars Odyssey; and BepiColombo). *MoonBEAM* would provide the IPN with the only dedicated GRB mission at > 150,000 km from the Earth, launched within within the past 20 years, and the

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[1] https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/ipn.html

only one outside of LEO with the capability of on-board transient localization. Figure 7 shows an example of how the IPN was used to determine the host galaxy for GRB 200415A, a MGF masquerading as a short GRB.

4. Summary

MoonBEAM provides essential gamma-ray observations of relativistic astrophysical transients with the following capabilities: instantaneous all-sky field of view from a lunar resonant orbit, >98% duty cycle, relatively stable background, sensitivity to prompt GRB emission energy range and broad coverage for spectroscopy. *MoonBEAM* also provides independent localization as well as a longer baseline for additional localization improvement with other gamma-ray missions, and rapid alerts to the astronomical community for contemporaneous and follow-up observations. *MoonBEAM*'s projected observations are 4,000+ gamma-ray transients with either detections or sensitive upper limits, enabling > 400 follow-up observations, > 1000 GRB detections, and all-sky limiting flux is 2x more sensitive than required to determine jet production rate in different progenitors. In the era of multimessenger astronomy instantaneous all-sky gamma-ray instruments are imperative. The full *MoonBEAM* Team author list can be found in [9].

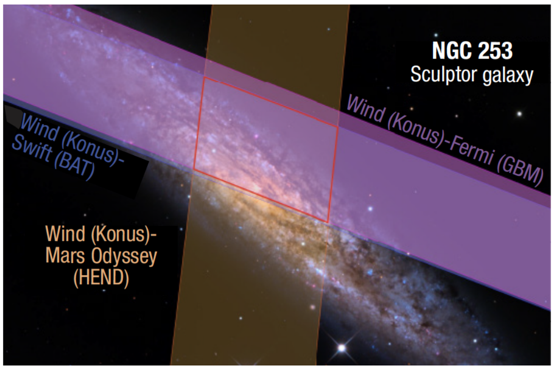

Figure 7: IPN localization of GRB 200415A, determined to be an MGF. The IPN used three gamma-ray instruments and found that the location of the MGF was the Sculptor Galaxy.

References

[1] Agostinelli, S., Allison, J., Amako, K., et al. 2003, Nucl. Instrum. Meth., 250

[2] Ahumada, T., Anand, S., Kumar, H., et al. 2021, GRB Coordinates Network, 30109, 1

[3] Connaughton, V., Briggs, M. S., Goldstein, A., et al. 2015, , 216, 32, doi: 10.1088/0067-0049/216/2/32

[4] Coughlin, M. W., Antier, S., Corre, D., et al. 2019, , 489, 5775, doi: 10.1093/mnras/stz2485

[5] Frontera, F., Amati, L., Costa, E., et al. 2000, , 127, 59, doi: 10.1086/313316

[6] Goldstein, A., Veres, P., Burns, E., et al. 2017, , 848, L14, doi: 10.3847/2041-8213/aa8f41

[7] Goldstein, A., Fletcher, C., Veres, P., et al. 2020, , 895, 40, doi: 10.3847/1538-4357/ab8bdb

[8] Howell, E. J., Ackley, K., Rowlinson, A., & Coward, D. 2019, , 485, 1435, doi: 10.1093/mnras/stz455

[9] Hui, C. M. 2023, "38th International Cosmic Ray Conference" No. 877

[10] Hurley, K., Pal'shin, V. D., Aptekar, R. L., et al. 2013, , 207, 39, doi: 10.1088/0067-0049/207/2/39

[11] Mong, Y. L., Ackley, K., Galloway, D. K., et al. 2021, , 507, 5463, doi: 10.1093/mnras/stab2499

[12] National Academies of Sciences, E., & Medicine. 2021, Pathways to Discovery in Astronomy and Astrophysics for the 2020s (Washington, DC: The National Academies Press), doi: 10.17226/26141

[13] Poolakkil, S., Preece, R., Fletcher, C., et al. 2021, , 913, 60, doi: 10.3847/1538-4357/abf24d

[14] Roberts, O. J. 2023, "38th International Cosmic Ray Conference" No. 1515

[15] Roberts, O. J., Veres, P., Baring, M. G., et al. 2021, , 589, 207, doi: 10.1038/s41586-020-03077-8

[16] von Kienlin, A., Meegan, C. A., Paciesas, W. S., et al. 2020, , 893, 46, doi: 10.3847/1538-4357/ab7a18

[17] Wanderman, D., & Piran, T. 2010, , 406, 1944, doi: 10.1111/j.1365-2966.2010.16787.x

[18] Wood, J. 2023, "38th International Cosmic Ray Conference" No. 881

[19] Zoglauer, A., Andritschke, R., & Schopper, F. 2006, , 50, 629, doi: 10.1016/j.newar.2006.06.049