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Moon Burst Energetics All-sky Monitor: A Beyond Earth-orbit Gamma-ray Burst Observatory

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Moon Burst Energetics All-sky Monitor (*MoonBEAM*) is a gamma-ray mission concept to observe the entire sky instantaneously for relativistic astrophysical explosions from a cislunar orbit. It is designed to explore the behavior of matter and energy under extreme conditions by observing the prompt emission from gamma-ray bursts, identifying the conditions capable of launching transient relativistic jets and the origins of high-energy radiation from the relativistic outflows. *MoonBEAM* will achieve uninterrupted, instantaneous all-sky coverage from 10 keV to 5 MeV by using phoswich gamma-ray detectors and operating from a cislunar orbit. This orbit will minimize Earth blockage and background variations that are difficult to reduce in Low Earth Orbit. *MoonBEAM* will provide essential prompt gamma-ray observations and rapid alerts to the astronomical community for contemporaneous and follow-up observations. This presentation will give an overview of the *MoonBEAM* mission and its mission design, which enable sensitive high-energy all-sky observation that is critical to the transient and multi-messenger astronomy.

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1. Introduction

MoonBEAM is a gamma-ray mission, deployed to cislunar space, designed to explore the behavior of matter and energy under extreme conditions by observing the prompt emission from relativistic astrophysical explosions. These transient bursts of emissions can be produced by the merger of two compact objects (neutron star or blackhole), a type of core collapse supernova known as a collapsar, or a giant flare generated by a magnetar, which is a neutron star with an extremely powerful, large-scale magnetic field. Relativistic transients are the most extreme phenomena in the known universe; they produce emissions across the entire electromagnetic spectrum and multi-messenger signals, encompassing photons, gravitational waves, neutrinos, and cosmic rays. Figure 1 shows the types of progenitors for these transients, which launch relativistic jets and ejecta that are responsible for the transient emissions. In this era of multi-messenger astronomy, simultaneous, broadband observations of relativistic transients are needed to construct a comprehensive picture of stellar explosions. These joint observations are crucial to studying the central engines that power the explosions, 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, identified as a critical part of the Astro2020 Decadal Survey [1] vision for the next decade in transient and multi-messenger astronomy (section 7.5.3.1 Time Domain Astrophysics Program and J.5.1 Time-Domain and Multi-Messenger Astrophysics), by reporting any prompt emission of a relativistic transient, and by providing rapid alerts to the astronomical community for contemporaneous and follow-up observations.

MoonBEAM is designed to answer key science questions from the Astro2020 Decadal Survey on compact objects and energetic phenomena with the following objectives:

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.

2. Key Mission Characteristics

MoonBEAM achieves instantaneous, all-sky coverage by positioning six gamma-ray detector assemblies at the corners of the spacecraft to minimize blockage (see Figure 2), and by deploying the observatory in an Earth-Moon Lagrange Point 3 cislunar orbit instead of Low Earth Orbit (LEO) to reduce particle background from radiation belts, atmospheric interactions, and planetary occultation from 30% to $<<$ 1% of the sky.

Each detector assembly consists of a 140-mm-diameter phoswich scintillator coupled to four closely packed, square flat-panel photo-multipliers. The phoswich scintillator uses a combination of Thallium-doped Sodium Iodide (NaI(Tl)) and Sodium-doped Cesium Iodide (CsI(Na)) crystals for both localization improvement and increased effective area for spectroscopy. It is sensitive to a broad energy range of 10–5,000 keV photons, with an energy resolution better than 12% at 662 keV. The instrument and scientific performance of *MoonBEAM* is further described in [2–4].

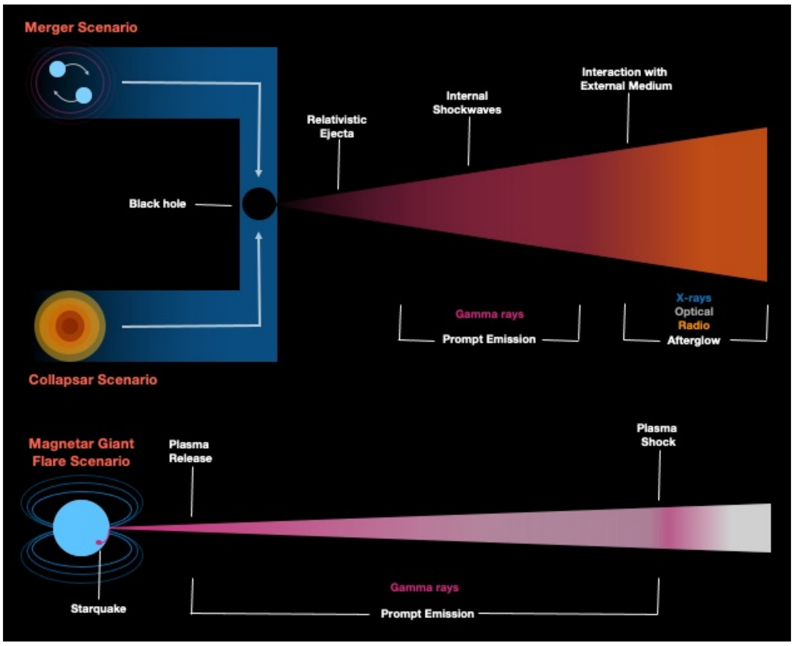

Figure 1: Three established progenitors have been confirmed to launch relativistic outflows. Prompt gamma rays probe the launching and emission mechanisms and are the first indication a relativistic transient has occurred. Signals from such relativistic transients cover the full electromagnetic spectrum and other messengers, observations of which are necessary to form a complete picture of the physical processes creating relativistic explosions and outflows.

The *MoonBEAM* science orbit is an Earth-Moon Lagrange Point 3 orbit, with a closest approach to Earth at over 200,000 km and a period of 27.6 days. This orbit provides the advantage of being away from Earth's limitations (occultation, higher particle background, etc.). At the science orbit, the Earth will occult $< 0.1\%$ of *MoonBEAM*'s field of view at any given time, compared to 30% for a mission in LEO. *MoonBEAM*'s orbit also has less radiation background components in comparison. Trapped particles in the Van Allen Belts, especially the South Atlantic Anomaly (SAA), the high-proton flux in the SAA inducing radioactive isotopes in gamma-ray instrument, and the secondary gamma rays and particles from cosmic ray interactions with the Earth's atmosphere are all eliminated at *MoonBEAM*'s distance from the Earth. Continuous data downlink capability remains available at this distance via the Near Space Network services that can support rapid alert notifications and provide the bandwidth needed for both time-tagged photons of triggers at 30μs resolution and continuously binned data at 64ms resolution for on-ground sub-threshold searches.

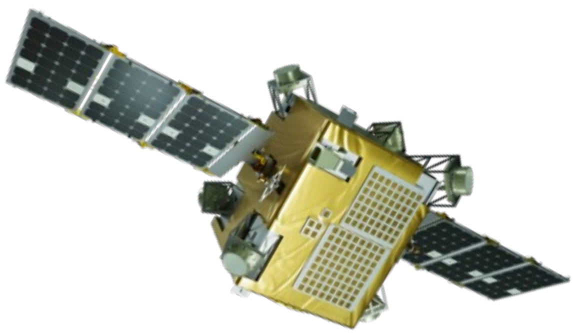

Figure 2: Six scintillating detectors positioned for an instantaneous all-sky field of view, no slewing required. Coupled with a cislunar orbit, *MoonBEAM* provides an unprecedented all-sky sensitivity that cannot be achieved in Low Earth Orbit.

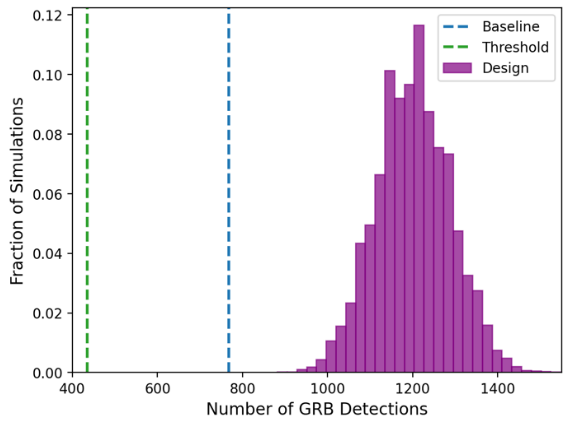

Figure 3: *MoonBEAM* expects to detect over 1000 GRBs over its 30-month science operation.

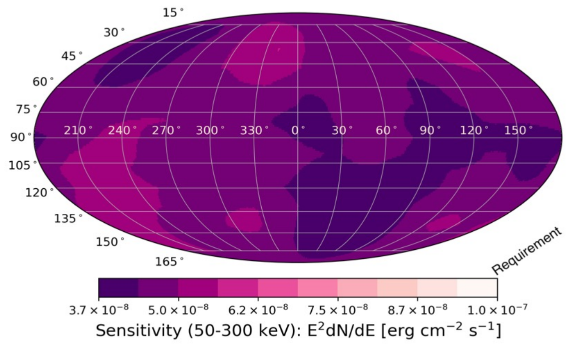

Figure 4: MoonBEAM's limiting flux sensitivity across the entire sky in any instant, providing the continuous sensitivity needed to study astrophysical jet formation and emissions.

Figure 3 showcases the predicted GRB detection distribution over 30 months of operation, derived from 10 years of GRB detections reported by the *Fermi* Gamma-ray Burst Monitor, coupled with the *MoonBEAM* instrument detection criteria and its expected background rates. In the absence of a detection, *MoonBEAM* provides unprecedented sensitive gamma-ray upper limits for any externally detected transients such as mergers seen in gravitational waves and supernovae detected in optical wavelengths, estimated to be in the order of thousands over the operation time of MoonBEAM. Figure 4 shows the limiting flux sensitivity of *MoonBEAM* across the entire sky.

The wide-field, sensitive, and continuous gamma-ray coverage is necessary to advance our current understanding of astrophysical jet formation, structure, and evolution. *MoonBEAM* achieves sensitivity improvement over current missions in LEO because of the combined advantage of its cislunar orbit and instrument design. It will join the Interplanetary Gamma-Ray Burst Timing Network (IPN) as one of the few missions outside of LEO with gamma-ray sensitivity, providing additional localization improvement potential via the timing triangulation method for any high-energy transients. *MoonBEAM* will be an integral mission for the IPN as the only dedicated GRB mission at 150,000+ km from the Earth launched within the past 20 years and the only one outside of LEO with the capability of on-board transient localization.

3. Summary

During *MoonBEAM*'s science operations in 2027-2030, it will provide continuous and instantaneous all-sky observations that cannot be achieved in Low Earth Orbit, and will measure the gamma-ray flux of thousands of transients that will occur during this time frame either through detections or sensitive upper limits. These unprecedented observations will advance our current understanding of the conditions and mechanisms that lead to the launching of relativistic jets from different progenitors, most of which remain unknown due to the lack of any preceding continuous and instantaneous all-sky sensitive monitoring of gamma-rays.

The *MoonBEAM* mission strategically aligns with the emergence of new discovery capabilities within the gravitational-wave network, neutrino observatories, and a myriad of telescopes that span the entire electromagnetic spectrum, all anticipated to be operational by the late 2020s. The complete suite of these observational tools is paramount in analyzing the central engines that power these explosive events, and in offering a deeper understanding of the physics underlying relativistic outflows.

References

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