Physics of the Cosmos

Future Innovations in Gamma rays Science Analysis Group

Report Status

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Program & Goals

- The purpose of this Science Analysis Group was to
  - Identify science priorities specific to space-based gamma rays
  - Clarify the current state of the art in theory, modeling, analysis and fundamental physics AND identify what that work requires from data in order to move forward impactfully
  - Identify new technologies and map them onto scientific priorities
  - Clarify what science can only be done with space-based gamma-ray missions and identify the capabilities they need to meet scientific goals
  - Identify synergies with multiwavelength, multimessenger and ground-based communities.
- In identifying our science priorities, it was important to define **what gamma-rays are the best at** - what is intrinsically gamma-ray science, and then to highlight how gamma rays serve the needs of other wavelengths and messengers.

NASA Astrophysics Big Questions

- How does the Universe work?
  - How do supermassive black holes form?
    - Gravitational Collapse - Dark Matter, most likely MeV/GeV signatures
    - Coevolution/Star Formation - GRBs, Blazars
    - Mergers - Pulsar Timing Array, probe different mass scales than LIGO/LISA.
- How did we get here?
  - Origin of Elements - Nucleosynthesis, MeV lines directly probe r-process decays.
  - Extreme Accelerators - Jetted Compact Objects (Pulsars, Magnetars, GRBs), Active Galaxies, Large-scale structures (Fermi bubble)
- Are we alone?
  - Gamma-ray host star activity impacts habitable zones

Executive Summary

- *Gamma rays probes the most extreme phenomena in our Universe: stellar death and birth of black holes, how they grow, where they reside, and how they are powered.*
- *The United States pioneered space-based gamma-ray astronomy in the 1960s and has led the field ever since. Without new NASA investment, this leadership will be ceded to China by the 2030s.*
- List of extraordinary discoveries in the past decades, made possible by continual US investment in high energy missions and tech development.
- Leading open topics uniquely address by gamma-ray observations:
  - Cosmic explosions -- What is their origin? What is the nature of the explosion engine and its underlying physics? What gets left behind across the history of the Universe?
  - Heavy elements in the Universe -- How are they produced? What is the underlying nuclear physics behind their production? How are they distributed and transported?
  - Supermassive black holes -- How do they form and grow? What are their jets made of? How do particles get accelerated to relativistic speeds and interact?
  - Fundamental physics – How does light behave under strong magnetic fields?

Key Science Questions

The following slides highlight what is in the report.
This is a template to develop a set of community slides for messaging and outreach.

1. What is the science question
2. Why you need gamma rays to answer this and how it is relevant to a non-gamma-ray person
3. What we know so far
4. What we need next

Key Science Questions: Gamma Ray Bursts I

1. Question/Goal: Neutron Star Mergers for Kilonova Studies
2. Why Gamma rays? Gamma rays provide prompt detection and localization for detailed kilonovae follow-up observations. Beyond ~100Mpc, gamma rays provide faster classification and triggering than gravitational waves. Gamma-ray spectral and temporal structures reveal engine power, jet structure, and the nature of the central engine.
3. Successes thus far: There are ~10 GRB-kilonova associations, only 1 has GW detection.
4. What we need:
   a. Observations: Wide to all-sky instantaneous field of view with sub-arcmin to deg-scale localization, timing accuracy to 30 micro-sec, with 10 micro-sec precision, keV-MeV energy range.
   b. Theory: An understanding of jet physics and afterglow models are needed. For follow-up studies, considerable work to maximize UVOIR observations is needed.

Key Science Questions: Gamma Ray Bursts II

1. Question/Goal: Star Formation throughout Cosmic Time
2. Why Gamma rays? GRB progenitors are the most massive stars and the GRB rate is sensitive to the initial mass function (IMF). Gamma rays can probe the production of GRBs to high redshift.
3. What we know thus far: Although uncertainties in the progenitor exist, GRBs have been used to probe star formation properties (disentangling formation rate and IMF dependencies). Gamma rays are required to discover these events.
4. What we need:
   a. Observations: Wide to all-sky instantaneous field of view with sub-arcmin to deg-scale localization, keV-MeV energy range.
   b. Theory: Better GRB progenitor studies accounting for GRB rates.

Key Science Questions: Supernova Engine

1. Question: How do supernova (SN) engines work? Critical in determining compact remnant formation (black holes and neutron stars), formation and dissemination of the elements.

2. Why Gamma rays? Gamma rays provide a nearly direct probe of the asymmetries in the inner SN ejecta set by the SN engine. X-ray, UVOIR observations limited by uncertainties in the plasma, atomic, shock and transport physics and contaminated by broad set of sources. Gamma-ray observations of ^{56}Ni, ^{57}Ni, ^{44}Ti, … focus on the engine itself (both thermonuclear and core-collapse supernovae).

3. Successes thus far: Gamma rays from ^{56}Ni decay in SN 1987A proved mixing, ^{44}Ti distribution in the Cas A SN remnant proved the role of convection.

4. What we need:
   a. Observations: Large observation sample – narrow-field instruments that can detect SNe to Virgo cluster; time-resolved to probe element distribution, high spectral resolution (~1%) to measure ejecta velocity distribution and distinguish decay lines.

   b. Theory: Improved explosion models, nuclear physics (bridges with nuclear physics community - Nuclear physics community is primed to address this)

Key Science Questions: Heavy Element Formation

1. Question: What are the production site(s) of r-process

2. Why Gamma rays? Uncertainties in explosive engines, power sources as well as plasma, atomic and transport physics make it difficult to probe r-process element production in kilonova. Gamma ray (and high energy X-rays, >30keV) of kilonova observations provide definitive identification of r-process isotopes.

3. Progress thus far: model predictions complete, no detections yet.

4. What we need:
   a. Observations: For remnant detection – wide-field with >100 sensitivity over COSI needed; To map remnant morphology, arcmin spatial resolution for ejecta distribution, ~1% energy resolution to measure Doppler shifted lines for 3D mapping.

   b. Theory: Although not needed for first detections, nuclear physics studies will improve exact analysis (goal of FRIB). Improved mass ejection models and nuclear physics allow astronomers to also probe explosion mechanisms.

Key Science Questions: Blazars

1. Question/Goal: Supermassive Black Hole Evolution (during the jetted AGN phase); Particle acceleration in jets for energy & CRs
2. Why Gamma rays? The nature of jet launching provides the jet composition. Jet composition is more uniquely probed (and less reliant on rare events) by MeV polarization. Blazar studies are usually multiwavelength endeavors that rely on survey data from Fermi, regardless of the community originating the study.
3. What we know so far: Blazar jets are at least partially leptonic (from lower energy data), but some have evidence of hadronic acceleration (from neutrinos).
4. What we need next: High effective area instrumentation in the MeV regime, ideally a wide FoV survey to reduce pointing bias associated with flares.

Key Science Questions: Gamma-Ray Pulsar Timing Array

1. Question/Goal: How do supermassive black holes form and merge? Are angular structures in the low frequency GW sky or individual sources?
2. Why Gamma rays? Pulsars timed in the gamma rays are free of most systematics (e.g. ISM and solar wind) compared to radio PTAs. GPTA times different and many pulsars on the sky for high GW angular resolution.
3. What we know so far: Radio PTAs are detecting a signal, we don't know what it is or whether it is even uniform on the sky. Radio telescopes are limited to one hemisphere.
4. What we need next: A high acceptance 0.1-5 GeV instrument with decent or good angular resolution and timing accuracy.

Key Science Questions: Photon Splitting

1. Question/Goal: Does photon splitting occur in nature as expected from QED?
2. Why Gamma rays? Photon splitting in astrophysical setting is best observed between 50 keV and 1 MeV, below pair production threshold where one photon can split into two in a strong magnetic field.
3. What we know so far: Magnetar spectra have to cut off somewhere below COMPTEL bounds – the shape of the cutoff and e
4. What we need next: Energy and magnetar rotational phase resolved polarization between 0.1-10 MeV.

Key Science Questions: Nature of Dark Matter

1. Why gamma rays? WIMPs: (i) Only probe of critical MeV-GeV energy range where thermal WIMP signatures happen (atmospheric absorption blocks ground-based detection below ~30 GeV). (ii) Retain complete spectral and spatial information (unlike neutrinos-weak interactions, poor directional reconstruction, or CRs - deflected by B fields) (iii) Complementary to direct detection: access to TeV-scale masses **beyond** underground lab sensitivity and probing **different** parameter space than accelerators. Axions/ALPs/dark photons/steral neutrinos/PBHs: spectral line signatures in MeV scales

2. Progress thus far: intriguing 2-3 sigma local excesses in 7 dwarfs for both $\bar{b}b$ and $\tau^+\tau^-$ channels; persistent Galactic center excess, ~3 sigma cross-correlation signal between gamma-ray background and galaxy overdensities

3. What we need?
   Observations: *angular resolution* <0.05°: resolve dwarf galaxy substructure, precision morphological studies of Galactic center excess; *energy resolution* <1% for MeV lines [<5% GeV-TeV]; effective area >30× Fermi-LAT: Detect thermal relic cross-sections across full WIMP mass range, achieve 5 sigma discoveries in reasonable mission lifetimes.
   Theory: (i) precise Galactic diffuse emission models to reduce systematic uncertainties; (ii) better understanding of dark matter substructure and density profiles; (iii) improved dark matter interaction modeling (self-interactions, Standard Model couplings)

JHEAP

- The JHEAP Special Issue is a collection of supporting articles and offers publication for novel efforts to calculate information cited in the report.
- Anyone can submit, but if you have an idea that you have not previously discussed with the FIGSAG Chairs, please let us know
    - Submission instruction: For this special issue, the appropriate article type is “VSI: FIGS.”. Do not designate an editor in the form.
- The JHEAP Special Issue submission deadline has been moved back to early March.

What's Next?

- Community thoughts on these key questions?
- Future SAG suggestions:
  - Particle acceleration in shocks to detail advances needed to achieve our long-term goals.
  - More detailed roadmapping of specific key science topics.
  - Preparation needed for the 2030 decadal.