ASTRO2020 SCIENCE WHITE PAPER

Gamma-Ray Science in the 2020s

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ✓ Multi-Messenger Astronomy and Astrophysics

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1 Introduction

Compact objects and their environments host physical processes in their most extreme conditions (e.g., highest densities, most intense magnetic fields, and highest velocities). These astrophysical sources typically have highly variable photon fluxes, evolving on time scales from several milliseconds to months. Some of these sources, such as Gamma-Ray Bursts (GRBs), release vast amounts of energy in only seconds. Compact objects emit over a broad range of wavelengths, but they are often particularly bright in the gamma-ray regime where their non-thermal energy spectrum peaks. This fast variability combined with broadband emission has made time-domain astrophysics an incredibly rich field.

Now, we know that these high-energy sources can also emit other cosmic messengers, such as gravitational waves, high-energy neutrinos, and cosmic rays. The recent discovery of a neutron star-neutron star binary merger with the simultaneous detection of a GRB and a gravitational wave signal, propelled us, in a day, from traditional astrophysics to the multi-messenger era. This discovery resulted in the largest multi-wavelength follow-up campaign of a high-energy source involving dozens of instruments world-wide. The discovery of high-energy neutrinos simultaneously with a gamma-ray flare emitted from a blazar-type Active Galactic Nucleus (AGN) confirmed the important role of gamma-ray astronomy in multi-messenger and time-domain astrophysics. High-energy studies are key to several areas where astronomy can probe fundamental physics, such as the formation of the heaviest elements, the evolution of the chemical composition of the universe across cosmic time, the geometry of space-time fabric, and the existence of dark matter, among other fundamental science.

With very large fields of view, the gamma-ray instruments are the ideal machines to lead in the multi-messenger era. In addition, in a decade where the large optical and radio surveys will collect hundreds of thousands of variable/transient sources a night, and where very-high energy ground-based gamma-ray telescopes will start to operate, gamma-ray space telescopes will be instrumental in constraining the nature of the transients and prioritizing follow-up observations. The unprecedented sensitivity of the new generation of gamma-ray instruments together with large fields of view, high-cadence sampling, accurate localization, polarization capabilities and high spectral resolution for nuclear line studies, will be keys for answering questions and challenges that modern astrophysics is facing.

2 Jets and Particle Acceleration (Cosmic Rays)

The accretion onto compact objects (super-massive black holes, stellar-mass black holes, or neutron stars) can power bipolar collimated plasma outflows (jets) that can move with bulk velocities approaching the speed of light. Charged particles in the ejected material (i.e., electrons, positrons, and baryons) can also reach relativistic energies via acceleration taking place at relativistic or mildly relativistic collisionless internal shocks, in shear or turbulent flows, and/or in magnetic reconnection. The radiation produced by the relativistic particles is non-thermal, broadband, and typically peaks in the gamma-ray regime. A good understanding of these acceleration processes is instrumental to probing matter at energies well beyond what is possible on Earth. γ-ray detectors with polarization capabilities would place definitive constraints on the emission processes, and, therefore, on the acceleration mechanisms, and on the composition of the jet. These jets can propagate to large distances and interact with the interstellar medium, thus producing shock waves or hot spots and lobes, as in the case of AGN. In particular, the interaction of jets emerging from neutron star mergers with the surrounding medium can produce relativistic shocks and form the heaviest elements via rapid neutron capture know as r-process for instance. Also, astrophysical jets emitted from GRBs and AGNs at high redshifts serve as probe of the intergalactic medium and provide information on the chemical evolution of the Universe; for instance, the attenuation of the high-energy γ-ray spectra when the γ-rays interact with the diffuse extragalactic background light informs on star formation and AGN activity.

Within a galaxy, charged particles released by compact object systems are accelerated to very high energies. These energetic galactic cosmic rays, whose origin remains partly debated, are crucial for regulating the evolution of galaxies. For instance, they maintain the structure of the galactic disk and alter the galactic magnetic fields, they contribute to the formation of the stars and protostellar disks, and they participate in maintaining a turbulent interstellar medium and forming complex molecules. One pressing question is the origin of the ultra-high energy cosmic rays with energies $\sim 10^8$ TeV; can they be accelerated up to such high energies in the jets of compact objects?

See for more detailed information:

• “Energetic Particles of Cosmic Accelerators I: Galactic Accelerators”, Tonia Venters, et al.
• “Energetic Particles of Cosmic Accelerators II: Active Galactic Nuclei and Gamma-ray Bursts”, Tonia Venters, et al.
• “Prompt Emission Polarimetry of Gamma-Ray Bursts”, Mark L. McConnell, et al.
• “High-Energy Polarimetry - a new window to probe extreme physics in AGN jets”, Bindu Rani, et al.
• “Multi-Physics of AGN Jets in the Multi-Messenger Era”, Bindu Rani, et al.
• “Supermassive black holes at high redshifts”, Vaidehi Paliya, et al.
• “Prospects for AGN Studies at Hard X-ray through MeV Energies”, Eileen Meyer, et al.

3 Nucleosynthesis and Radioactive Decay

Fundamental open questions concerning the formation of heavy elements in the universe, the evolution of the chemical composition of galaxies, and the ultimate stages of stellar objects, among others, can be answered by studying nuclear processes such as radioactive decay, nuclear de-excitation, and positron annihilation. Fast-cadence high-resolution spectroscopy in the MeV γ-ray regime is a unique way of probing these nuclear processes, and current technologies can make such measurements a reality. For instance, the study of MeV nuclear lines will inform on the formation of stable heavy elements produced by relatively nearby (3-10 Mpc) neutron star mergers via r-process, the mixing of newly synthesized elements within galaxies, the distribution of ^{56}Ni from Type Ia Supernovae (SNIa), the production of heavy elements in novae, and how white dwarfs and massive stars explode as SNIa and core-collapse supernovae, respectively. Answers to many of these questions would also benefit from multi-wavelength observations initiated by γ-ray detections.

See for more detailed information:

• “Catching Element Formation In The Act—The Case for a New MeV Gamma-Ray Mission: Radionuclide Astronomy in the 2020s”, Chris L. Fryer, Frank Timmes, Aimee L. Hungerford, Aaron Couture, et al.

4 Gravitational Waves

Gravitational-waves originate primarily from compact objects whose initial electromagnetic detection is obtained in the γ-ray regime where their energy spectra typically peak; therefore, γ-ray astronomy is a natural partner of the large gravitational-wave consortia. Simultaneous gravitational-wave and γ-ray detections provide the full picture of a binary neutron-star merger in revealing the nature of the system before the stellar compact object forms, the nature of the central engine, the energy reservoirs (internal or magnetic) powering the astrophysical jets, the acceleration mechanisms and magnetic fields driving the particle within the jet, and the interaction of the jet with the interstellar medium.

The next upgrades of gravitational-wave detectors will increase their sensitivity and, consequently, the volume they will probe. These progresses must be accompanied by new γ-ray instruments which must have very large field of views and the sensitivity to probe the same volume. The simultaneous gravitational-wave and γ-ray detection of GW 170817 and GRB 170817A, respectively, triggered the largest multi-wavelength follow-up campaign involving dozens of instruments world-wide. This resulted in major scientific results with a single event, such as the origin of stable heavy elements via the r-process for instance. Gravitational-wave/γ-ray astrophysics will open a door for studying fundamental physics, including the geometry of space-time fabric at both small and large scales.

See for more detailed information:

• "Gamma Rays and Gravitational Waves", Eric Burns, et al.
• "A Summary of Multimessenger Science with Neutron Star Mergers", Eric Burns, et al.

5 Dark Matter and Fundamental Physics

About 80% of the matter contained in our universe is of non-baryonic nature: Dark Matter (DM). Two leading particle candidates for DM are the Weakly Interacting Massive Particles (WIMPs) and the Weakly Interacting Sub-eV Particles (WISPs) like axions and axionlike particles. DM particle annihilation is believed to imprint different signatures in the γ-ray spectral energy band. Such an indirect detection requires a complete scan of the γ-ray energy range, which has been initiated with the Large Area Telescope (LAT) on-board the Fermi Gamma-ray Space Telescope. Although a possible signal has been observed at the galactic center, the source confusion due to the limited angular resolution of the LAT makes impossible to identify the origin of the excess, which may be due to DM particle annihilation or to an unresolved population of pulsars, for instance. DM is a major missing piece in our understanding of the composition of the universe. The hunt for DM must continue with indirect detection using γ-ray space telescopes with high spatial resolution and high sensitivity, in combination with direct detection searches in particle accelerators, and indirect observational evidences such as the Bullet Cluster. All these messengers will be the key for proving the existence and the nature of DM particles.

See for more detailed information:

• "Looking Under a Better Lamppost: MeV-scale Dark Matter Candidates", Tim Linden, Regina Caputo, et al.

6 Conclusion

Through observations of compact objects, their formation, and their environments, we obtain information that allows us to test the laws of physics in the most extreme conditions, to track the evolution of the chemical composition of the Universe, to study the origin of the heaviest elements, and to probe the geometry of space-time fabric at small and large scales. Although compact objects in various stages of their lives, radiate at all frequencies and emit all types of messengers, high-energy astronomy is the cornerstone to decipher these cosmological encrypted messages. With very large fields of view, high-cadence sampling, high angular and spectral resolutions, and polarization capabilities, γ-ray instruments are mature and ready to take the challenge, and they are essential for the time-domain multi-messenger era. In particular, space γ-ray missions are needed for catching the GRBs that come with gravitational waves or the blazar flares that come with high-energy neutrinos. They will also complement the scientific results that will be collected with the ground-based Cherenkov Telescope Array and the large optical and radio surveys such as the Large Synoptic Survey Telescope and Square Kilometre Array.

For a comprehensive presentation of the science topics that the γ-ray space community identified as key priorities and projects for the next decade, please read:

• "Energetic Particles of Cosmic Accelerators I: Galactic Accelerators", Tonia Venters, et al.
• "Energetic Particles of Cosmic Accelerators II: Active Galactic Nuclei and Gamma-ray Bursts", Tonia Venters, et al.
• "Neutrinos, Cosmic Rays, and AMEGO", Roopesh Ojha, et al.
• "Prospects for Galactic Cosmic Rays, Interstellar Medium, and Associated Gamma-Ray Emission Studies at MeV-GeV Energies", Elena Orlando, et al.
• "Prompt Emission Polarimetry of Gamma-Ray Bursts", Mark L. McConnell, et al.
• "High-Energy Polarimetry as A New Window to Unveil Cosmic Rays and Neutrinos in AGN Jets", Bindu Rani, et al.
• "Multi-Physics of AGN Jets in the Multi-Messenger Era", Bindu Rani, et al.
• "Prospects for AGN Studies at Hard X-ray through MeV Energies", Eileen Meyer, et al.
• "A Unique Messenger to Probe Active Galactic Nuclei: High-Energy Neutrinos", Sara Buson, et al.
• "Supermassive black holes at high redshifts", Vaidehi Paliya, et al.
• "Catching Element Formation In The Act—The Case for a New MeV Gamma-Ray Mission: Radionuclide Astronomy in the 2020s", Chris L. Fryer, et al.
• "Gamma rays and Gravitational Waves", Eric Burns, et al.
• "A Summary of Multimessenger Science with Neutron Star Mergers", Eric Burns, et al.
• "Looking Under a Better Lamppost: MeV-scale Dark Matter Candidates", Tim Linden, et al.
• "Prospects for Studies of Pulsars at MeV Energies", Alice Harding, et al.
• "Magnetars as Astrophysical Laboratories of Extreme Quantum Electrodynamics: The Case for a Compton Telescope", Zorawar Wadiasingh, et al.
• "Prospects for detection of synchrotron halos around middle-age pulsars",Mattia Di Mauro et al.
• "Prospects for MeV Observations of PWNe", Joseph Gelfand et al.
• "Positron Annihilation in the Galaxy", Carolyn Kierans, et al.
• "Measurement of the Optical-IR Spectral Shape of Prompt Gamma-Ray Burst Emission: A Timely Call to Action for Gamma-Ray Burst Science", Bruce Grossan, et al. (proposed add-on to a wide-field γ-ray mission)