GRIPS - The potential of a future MeV survey

J. Greiner\(^{(1)}\), G. Kanbach\(^{(1)}\), K. Mannheim\(^{(2)}\)
and the GRIPS collaboration\(^{*}\)

\(^{(1)}\) Max-Planck Institut für extraterrestrische Physik, 85740 Garching, Giessenbachstr. 1, Germany
\(^{(2)}\) Würzburg Univ., Am Hubland, D-97074 Würzburg, Germany

**Summary.** — We describe the potential of GRIPS, a future MeV mission. The Gamma-Ray Imaging, Polarimetry and Spectroscopy (“GRIPS”) concept combines a Compton and pair telescope, and will be a very sensitive polarimeter. GRIPS would perform a continuously scanning all-sky survey from 200 keV to 80 MeV achieving a sensitivity which is better by a factor of 40 compared to the previous missions in this energy range.

PACS 00.00 +26.50.+x, 95.30.Gv, 95.55.Ka, 95.85.Pw.
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1. – Introduction: The MeV gap

The photon energy range between hard X-rays of 0.2 MeV and γ-rays of 80 MeV covers the prime range of nuclear excitation and binding energies. Many high energy sources have their peak emissivity in this regime, which therefore is as important for high-energy astronomy as optical astronomy for phenomena related to atomic physics. In addition, it includes the energy scale of the electron and pion rest mass. The “MeV-gap” in current instrument sensitivity stretches exactly over this range (Fig. 1). The GRIPS mission [1] will improve the sensitivity in this gap by a factor of 40 compared to previous missions. Therefore, the GRIPS all-sky survey with γ-ray imaging, polarimetry, and spectroscopy holds a high promise of new discoveries and of precision diagnostics of primary high-energy processes.

The scientific scope of the mission is centered on the themes “The Evolving Violent Universe” and “Matter under extreme conditions” of the Cosmic Vision strategic plan, pertaining to the astrophysics of the most extreme objects in the Universe in which the plasma becomes relativistic, nuclear interactions and radioactive decays take place, and where particle acceleration plays a major role in the energy budget.

\(^{*}\) www.grips-mission.eu
Fig. 1. – GRIPS will allow a major sensitivity improvement in an energy range (between hard X-rays and GeV γ-rays) which has been poorly explored, yet holds unique information for a wide range of astrophysical questions. The curves are for an exposure of $10^6$ sec, $\Delta E = E$, and an $E^{-2}$ spectrum.

GRIPS will open the astronomical window to the bizarre and highly variable 0.2–80 MeV sky, to investigate fascinating cosmic objects such as γ-ray bursts, blazars, supernovae and their remnants, accreting binaries with white dwarfs, neutron stars or black holes often including relativistic jets, pulsars and magnetars, and the often peculiar cosmic gas in their surroundings. Many of these objects show MeV-peaked spectral energy distributions or characteristic spectral lines; we target such primary emission to understand the astrophysics of these sources.

2. – The Mission

GRIPS will combine a Compton and pair telescope based on the latest developments in nuclear and high-energy physics laboratories (Fig. 2). Modern 3D position-sensitive and space-proven detectors with advanced (nanosecond level) readout technology will ensure unprecedented background rejection capability [2] and thus guarantee the above sensitivity leap. Taking advantage of the Compton-scattering physics, GRIPS will also be a very sensitive polarimeter [3]. The energy resolution of 3% at photon energies of 1 MeV renders the gamma-ray telescope ideal for the study of broadened emission lines from explosive sources such as supernovae; and with the extended spectroscopic performance throughout the entire nuclear energy range we will be armed for pioneering
astrophysical studies of nuclear excitation and resonance absorption lines. The limitation in imaging resolution which is intrinsic to the detection physics in the MeV band will be compensated by detecting secondary emission from the same sources with auxiliary X-ray and NIR telescopes with their sub-arcmin angular resolutions.

GRIPS should be launched into a low-altitude, equatorial orbit (LEO) to minimize the background. GRIPS consists of two satellites, flying in a “close-pair” configuration (Fig. 3): one satellite with the Gamma-Ray Monitor (GRM), the other with an X-Ray Monitor XRM and an Infra-Red Telescope (IRT). Both satellites should be 3-axis stabilized. The gamma-ray telescope/satellite of GRIPS will be continuously pointing at the zenith, thus monitoring ca. 80% of the sky over each orbit for transient events, including gamma-ray bursts. The X-ray/infrared telescope satellite should have the capability of autonomously slewing for follow-up observations of gamma-ray bursts. As added value, the mission will deliver positions and fluxes of transient alerts to the community. For gamma-ray bursts, bursts in the redshift range $7 < z < 35$ will be recognized within minutes by IRT, and this information also transmitted to ground in near-real-time. We anticipate a lifetime of 10 years. The prime instrument will use 500 kg of LaBr$_3$ scintillator crystals, and the total satellite weight is about 5 tons. The launcher should be a Soyuz-Fregate rocket launched from Kourou. The spacecraft busses should provide 1.8/1.1 kW power and 40 Mbps telemetry bandwidth.
3. – Scientific Themes

**Gamma-Ray Bursts and First Stars:** Unrivaled by any other method, the detection of highly penetrating $\gamma$-rays from cosmological $\gamma$-ray bursts will shed light on the first massive stars and galaxies which formed during the dark ages of the early Universe. With its energy coverage up to 80 MeV, GRIPS will firmly establish the high energy component seen in addition to the canonical Band function in one CGRO/EGRET (>10 MeV) and one Fermi/LAT burst (>100 MeV) in much larger numbers, and characterize its origin through polarisation signatures. GRIPS will measure the degree of polarisation of the prompt $\gamma$-ray burst emission to a few percent accuracy for more than 10% of the detected GRBs, and securely measure how the degree of polarisation varies with energy and/or time over the full burst duration for dozens of bright GRBs. Also, the delay of GeV photons relative to emission at $\sim$ hundred keV, observed in a few GRBs with Fermi/LAT, manifests itself already at MeV energies in Fermi/GBM, and will thus be a science target for GRIPS. These observations enable a clear identification of the prompt GRB emission processes, and determine the role played by magnetic fields.

GRIPS will detect about 650 GRBs yr$^{-1}$, a large fraction of these at high-redshift ($\sim$30 GRBs yr$^{-1}$ at $z > 5$, and $\sim$22 GRBs at $z > 10$). The 7-channel near-infrared telescope (IRT) will improve the localization to the required arcsecond level and will determine photometric redshifts for the bulk of the most distance ($z > 7$) sources. It will allow to measure the incidence of gas and metals through X-ray absorption spectroscopy and line-of-sight properties by enabling NIR spectroscopy with JWST.

If the GRB environments contain total hydrogen column densities of $10^{25}$ cm$^{-2}$, or higher, GRIPS holds the promise of measuring redshifts directly from the $\gamma$-ray spectrum via nuclear resonances, and will be sensitive to do so beyond $z\sim$13.

GRIPS will also detect a handful of short GRBs at $z < 0.1$, enabling a potential discovery of correlated gravitational-wave and/or neutrino signal.
Blazars: GRIPS will catalogue about 2000 blazars, probing blazar evolution to large redshifts. These observations will pinpoint the most massive halos at large redshifts, thus severely constraining models of structure evolution. This large sample will establish their (evolving) luminosity function and thus determine the fractional contribution of blazars to the diffuse extragalactic background. GRIPS is expected to detect \( \sim 10 \) blazars at \( z > 8 \). Studies of the nonthermal radiation mechanisms will be supported through spectro-polarimetric measurements. The link between the inner accretion disk and the jet can be probed with correlated variability from the thermal to the nonthermal regime, using GRIPS auxiliary instruments. This will localize the region of high-energy emission.

Supernovae and Nucleosynthesis: The primary energy source of supernova (SN) light is radioactive decay. The first direct measurement of the nickel and cobalt decay in Type Ia SNe will pin down their explosion physics and disentangle their progenitor channels. This will impact the luminosity calibration of Type Ia SNe that serve as standard candles in cosmology. The otherwise unobtainable direct measurement of the inner ejecta and the explosive nucleosynthesis of core collapse supernovae will allow to establish a physical model for these important terminal stages of massive-star evolution. Explosion asymmetries and the links to long GRBs are important aspects herein. The fraction of nearby pair-instability supernovae from very massive stars will be unambiguously identified through their copious radioactivity emission. All these observations will be crucial for complementing neutrino and gravitational wave measurements, and for our understanding of cosmic chemical evolution.

Cosmic Rays: Nuclear de-excitation lines of abundant isotopes like \( ^{12}\text{C} \) and \( ^{16}\text{O} \), the hadronic fingerprints of cosmic-ray acceleration, are expected to be discovered with GRIPS. Understanding the relative importance of leptonic and hadronic processes, and the role of cosmic rays in heating and ionizing molecular clouds will boost our understanding of both relativistic-particle acceleration and the cycle of matter.

Magnetars: The detection of instabilities in the supercritical magnetospheres of magnetars, which are expected to lead to few-hundred keV to possibly MeV-peaked emission, will explore white territory on the field of plasma physics.
Annihilation of Positrons: GRIPS will probe positron escape from candidate sources along the galactic plane through annihilation $\gamma$-rays in their vicinity. For several microquasars and pulsars, point-source like appearance is expected if the local annihilation fraction $f_{\text{local}}$ exceeds 10% ($I_\gamma \sim 10^{-2} \cdot f_{\text{local}} \text{ ph cm}^{-2} \text{s}^{-1}$). GRIPS will enable the cross-correlation of annihilation $\gamma$-ray images with candidate source distributions, such as $^{26}$Al and Galactic diffuse emission above MeV energies (where it is dominated by cosmic-ray interactions with the ISM) [both also measured with GRIPS at superior quality], point sources derived from INTEGRAL, Swift, Fermi, and H.E.S.S./MAGIC/VERITAS/CTA measurements, and with candidate dark-matter related emission profiles. GRIPS will deepen the presently best INTEGRAL sky image by at least an order of magnitude in flux, at similar angular resolution. Comparing Galactic-disk and -bulge emission, limits on dark-matter produced annihilation emission will constrain decay channels from neutralino annihilation in the gravitational field of our Galaxy. GRIPS will also perform sensitive searches for $\gamma$-ray signatures of dark matter for nearby dwarf galaxies.

Solar Flares: Solar flares will be a natural by-product of the continuous sky survey carried out by GRIPS since the Sun passes regularly through its field of view. Gamma-rays in the MeV regime provide the means to directly probe particle acceleration and matter interactions in these magnetised, non-thermal plasmas. Polarisation measurements are of great value for disentangling these dynamic processes.

4. – Conclusion

We have the following burning questions: How do stars explode? What is the structure of massive-star interiors and of compact stars? How are cosmic isotopes created and distributed? How does cosmic-ray acceleration work? How is accretion linked with jets? Answering these questions will provide the basis to understand the larger astrophysical scales, like the interstellar medium evolution in galaxies, the supernova-fed gas in galaxy clusters, and the cosmic metallicity evolution. This bottom-up approach will also help in reaching other ambitious goals of the Cosmic Vision plan which addresses the challenging fundamental physics near event horizons, and cosmological questions which may carry us beyond standard astrophysics as we know it today. GRIPS will be an extraordinary tool to advance the study of the nonthermal and violent Universe.

The GRIPS mission would provide the data to answer key questions of high-energy astrophysics. Moreover, the all-sky survey with an expected number of more than 2000 sources, many of them new, will at the same time serve a diversity of communities for the astronomical exploration of so-far unidentified X/$\gamma$-ray sources and of new phenomena. This will strengthen ESA’s outstanding heritage in pioneering space research. The delivery of triggers on bursting sources of high-energy emission will amplify the scientific impact of GRIPS across fields and communities. As the 2010 Decadal Survey Report of the US Academy of Science puts it, “Astronomy is still as much based on discovery as it is on predetermined measurements.”

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