PROCEEDINGS OF SCIENCE

Exploring the Universe from hard X-rays to gamma rays with GRIPS

Karl Mannheim[1] **and Jochen Greiner**[2] **(for the GRIPS consortium)***

[1] *Institut für Theoretische Physik und Astrophysik, Am Hubland, D-97074 Würzburg, Germany*
Email: mannheim@astro.uni-wuerzburg.de

[2] *Max-Planck-Institut für extraterrestrische Physik, D-85741 Garching, Germany*
Email: jcg@mpe.mpg.de

The Universe is still largely unexplored between hard X-rays and 100 MeV gamma rays. Using advanced detector technology, the combined pair and Compton telescope GRIPS can achieve a sensitivity improvement by a factor of up to 40 compared with previous observatories. The gamma ray imaging, polarimetry, and spectroscopy mission GRIPS would be a pathfinder in the transient Universe, discovering the most redshifted gamma ray bursts and blazars, detecting for the first time the primary ^{56}Ni from supernovae, identifying sources of cosmic ray nuclei, exploring white territory in the plasma chart by measuring the emission of magnetars, and resolving the structure of the enigmatic pair halo of our Galaxy.

25th Texas Symposium on Relativistic Astrophysics - TEXAS 2010
December 06-10, 2010
Heidelberg, Germany

*www.grips-mission.eu

PoS(Texas 2010)249

1. Introduction

The MeV-gap marks the part of the electromagnetic spectrum defined by the fundamental scales of the electron rest mass at 511 keV, the nuclear binding energy at ~ 1 MeV, and the pion rest mass at 70 MeV. A large number of astrophysical sources show a peak in their spectral energy distribution at MeV energies, and a wealth of nuclear emission lines still awaits to be discovered with sensitive instruments. The COMPTEL mission onboard CGRO and INTEGRAL have pioneered the field of MeV astronomy which still in its infancy. They have provided the first catalogues of soft gamma-ray sources [1, 2, 3, 4] and an Al-26 all-sky map showing the Galactic supernova history [5]. The diversity of the types of sources found is suprisingly large, including low- and high-mass accreting binaries, pulsars and pulsar wind nebulae, magnetars, cataclysmic variables, novae, radio galaxies, blazars, Seyfert galaxies, or the Coma cluster of galaxies. Some of the sources show up at still higher energies where the observational coverage is currently provided by FERMI-LAT ($>$ 200 MeV) and the ground-based imaging telescopes such as H.E.S.S., MAGIC, and VERITAS ($>$ 100 GeV.) The future could bring us unprecendented coverage of the electromagnetic spectrum and superior sensitivity with GRIPS (200 keV to 80 MeV), Gamma-400 (30 GeV to 1 TeV), and CTA (100 GeV to 100 TeV).

The prevalence of gamma rays generally shows non-thermal plasma conditions which play a key role for the energy release from compact sources, presumably due to magnetic fields ordered by rotation. The realm of the extremes accessible in the MeV gap is central to the fields of nuclear astrophysics, the physics of cosmic rays, high-energy astrophysics, and astroparticle physics. MeV observations will eventually reveal the places of heavy-element nucleosynthesis and the sources of cosmic ray protons and ions, will observe the innermost regions of accreting compact sources, constrain light dark matter models, and explore uncharted territory in plasma physics. In the emerging era of gravitational wave astronomy, an all-sky MeV monitor provides the ultimate cross-check for the discovery of supernovae and merging neutron stars or black holes.

In these proceedings, we describe the gamma ray imaging, polarimetry, and spectroscopy mission GRIPS as it has been proposed to ESA in the frame of the medium-sized mission program. We highlight the scientific showcase for some key science topics that could be addressed with GRIPS and give a brief outlook.

2. Instruments

2.1 Overview

Building on the experience gained with the MEGA detector developed at MPE [6], the Gamma Ray Monitor (GRM) has been designed for an all-sky survey mission GRIPS [7]. GRIPS will carry three major telescopes: the GRM, the X-Ray Monitor (XRM) based on the eROSITA telescope and the Infrared Telescope (IRT) based on the EUCLID mirror. GRM is a combined Compton scattering and pair creation telescope sensitive in the energy range 0.2-80 MeV, and will achieve a factor of 40 improvement in sensitivity compared to previous missions. The auxiliary instruments provide arcmin positions and near-infrared photometric redshifts in the range $7 < z < 35$ for gamma ray bursts . In a continuous zenith pointing mode, a 5-year gamma-ray all-sky survey with GRIPS will catalogue 3300 GRBs, 2000 blazars and 300 Seyfert galaxies, and 50 pulsars (including AXPs).

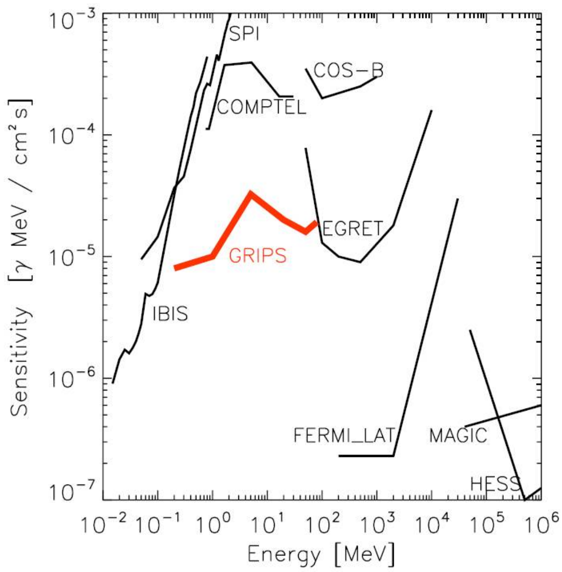

Figure 1: Sensitivity of GRIPS for a survey with an exposure of 10^6s ($\Delta E = E$, $dN/dE \propto E^{-2}$).

Furthermore, GRIPS is expected to discover 20 supernovae (SNIa and core-collapse SN). Many more types of sources such as supperbubbles, accreting binaries, clusters of galaxies, or flare stars are theoretically expected to show up in the survey.

2.2 Compton- and pair telescope

In the energy band from 200 keV to 100 MeV, the dominant process for the scattering of gamma rays with typical detector materials changes from Compton scattering to pair production at ~ 8 MeV. Therefore, the energies and directions of the secondaries from both types of interaction must be determined with great accuracy to reconstruct the incident primary photon properties. A good performance can be achieved with a two-level detector comprising a tracker and calorimeter, protected by an anti-coincidence shield made out of plastic scintillator and read out with avalanche photo diodes. In Compton scattering events, the incident photon scatters off an electron in the tracker where the point of interaction and the energy imparted to the electron is measured. The tracker consists of 64 layers each containing a mosaic of double-sided Si strip detectors spaced at a distance of 5mm. The scattered photon interaction point and energy are recorded in the calorimeter which is made out of $LaBr_3$ prisms read out with Si drift diodes. From the positions and energies of the two interactions the incident photon angle is computed from kinematics. The primary photon incident direction is then constrained to a celestial circle. For incident energies above ~ 2 MeV the recoil electron typically receives enough energy to penetrate several layers of the tracker, allowing it to be tracked. This constrains the incident direction of the photon to a short arc on the event circle better than 1°. Since the Klein-Nishina cross section is strongly polarization dependent, the scattered photons preferentially lie in a plane perpendicular to the direction of the electric-field vector of the incoming photon. Thus, a Compton telescope with a calorimeter covering a large solid angle is a unique polarimeter. In the case of pair production, the incident photon converts into an electron-positron pair in the tracker. These two particles are tracked and determine the incident

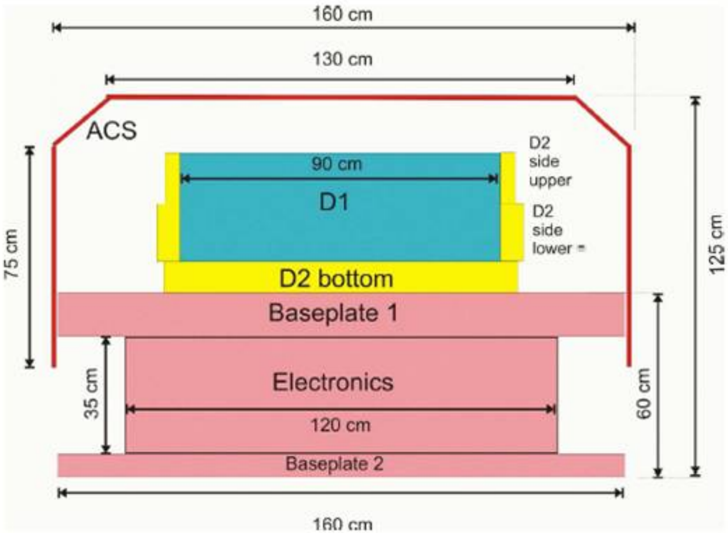

Figure 2: Schematic drawing of the GRB detector with the tracker D1, the calorimeter D2, and the anti-coincidence shield ACS.

photon direction. The total energy is measured by absorption in the tracker or the calorimeter for spectroscopy. Simulations using the Megalib software suite [8] show that the performance of the detector represents a big leap forward from the previous missions. Some key parameters at 1.8 MeV are the effective area of 195 cm^2, the field of view of 45 1°, the energy resolution of 17 keV, the angular resolution of 1.8 °, and the narrow-line sensitivity of 1.5×10^{-6} $cm^{-2}s^{-1}$ for an exposure of 10^6 s.

2.3 Launch and orbit requirements

Including the auxiliary instruments, GRIPS will weigh 5.1 t , thus requiring a launcher that can bring it into an equatorial, circular, low-Earth orbit (LEO) with an altitude of 500 km, and correspondingly more in a joint mission with complementary instruments. The LEO is essential to establish a low background, high science data fraction per orbit, a high downlink rate for the data transmission, and a long duration of the orbit over an anticipated lifetime of up to 10 years. A low background also means low inclination, preferably 0° to avoid the radiation belts and the South Atlantic Anomaly. It is now well established that the background in hard X-ray and gamma-ray instruments in a LEO can be a factor of 100 lower than in a Highly Eccentric Orbit, such as that of INTEGRAL.

3. Science goals

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". An all-sky survey at MeV energies holds the promise for both, new discoveries and precision tests of fundamental building blocks for our understanding of the non-thermal Universe. The scientific scope of the mission is

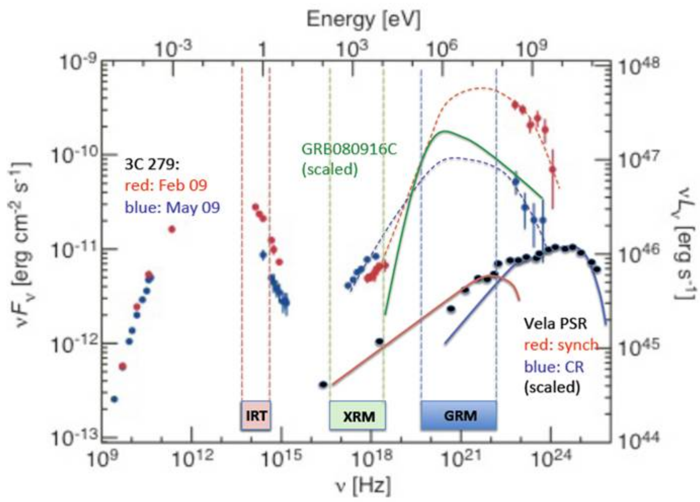

Figure 3: Examples of spectral energy distributions of non-thermal sources peaking at MeV energies.

centered on the themes "Evolving Violent Universe" and "Matter under extreme conditions" of ESA's 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. The GRIPS mission will be an encounter with the superlatives:

Highest redshifts: *Trace the first massive stars through GRBs and the first massive dark matter halos with MeV blazars.* GRIPS will observe in the energy range where GRB emission peaks. With its energy coverage up to $\sim$ 100 MeV, GRIPS will firmly establish the high energy component seen in one CGRO/EGRET (>10 MeV) and one Fermi/LAT burst (>100 MeV) in much larger numbers, and characterize its origin through polarization signatures. GRIPS will detect a large fraction of GRBs at high redshifts, and measure metal abundances through X-ray and NIR absorption spectroscopy. GRIPS should detect more than 20 GRBs at z > 8. If the GRB environments contain total hydrogen column densities higher than 10^{25} cm^2 , GRIPS could measure redshifts directly from the gamma-ray spectrum via nuclear resonances, and will be sensitive to do so beyond $z > 13$ [9]. GRIPS will also detect a handful of short GRBs at low redshifts, enabling a potential discovery of correlated gravitational-wave and/or neutrino signal. GRIPS will also catalogue about 2000 blazars [10], 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 of blazars 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.

Beyond the thermal regime: *Study the transition of thermal disks to non-thermal jets and the injection of cosmic rays.* Studies of non-thermal radiation mechanisms in compact sources and the link between accretion disks and jets will be possible through spectro-polarimetric measurements and multi-wavelength monitoring. GRIPS will observe diffuse nuclear de-excitation lines and inverse-Compton emission from the inner Galaxy, probing the CR-ISM connection with unprecedented sensitivity. Furthermore, nuclear deexcitation lines expeted from Wolf-Rayet supernova remnants, such as Cas A (cf. Tibolla et al., this volume), could be discovered. Nuclear deexcitation lines of abundant isotopes like ^{12}C and ^{16}O produced in the environments of SNRs and accreting binaries offer unique laboratories for gauging models of cosmic ray production, acceleration, transport, and interaction with their surroundings. GRIPS will establish this tool for particle acceleration sites in the Galaxy. GRIPS will search for long orbit neutron star/massive star binaries and for tight accreting systems harboring neutron stars or black holes. These systems (e.g. Cyg X-1) exhibit hard power-law spectral tails beyond 100 keV when they are in their low/hard emission state. It is important to determine how these hard power laws continue into the MeV range, because spectral features (lines, breaks, cut-offs) are unique fingerprints of nonthermal particle populations expected in those sources. GRIPS will probe accretion physics in the high-energy domain of stellar black holes, thus aid our understanding of the more-extreme circumstances encountered in accretion onto supermassive black holes.

Extreme explosions: *Decipher the explosion mechanisms of SNe and GRBs and the formation of elements.* GRIPS will search the nearby Universe out to 20 Mpc for ^{56}Ni decay gamma-ray lines from SNIa, with an expected $10-20$ significant detections. Establishing ratios of various lines from the ^{56}Ni decay chain and their variation with time, are key GRIPS objectives. Even if the lines are significantly Doppler broadened, the 0.1-3 MeV continuum can be used to test different explosion scenarios. Combined with optical-IR data, one can determine the amount of unburned white dwarf material, and with annihilation lines from ^{56}Co and ^{48}V decay positrons, one has a sensitive probe (via e^+ propagation) of the magnetic field structure in expanding SNIa remnants. GRIPS will also detect 3-5 nearby core-collapse supernovae (ccSNe). As for SNIa and SN1987A, the gamma-ray escape from the ejecta reflects hydrodynamic large scale mixing during and after the explosion. Comparing the gamma-ray characteristics of different classes of SNe, including pair-instability supernovae (due to their high ^{56}Ni mass), and 1-2 hyper-energetic SNe linked to GRBs, GRIPS will probe potentially large variations in their progenitors, and offer a direct view of their central engines.

Antimatter: *Find the sources of positrons and constrain light dark matter.* GRIPS will probe positron escape from sources along the galactic plane through annihilation gamma-rays in their vicinity. For several microquasars and pulsars, point-source like appearance can be expected. 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. measurements of pulsars and accreting binaries, and with candidate dark-matter related emission profiles, will reveal the origins of the Galactic positronium. 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 through inverse-Compton scattering off the microwave background. GRIPS will also perform sensitive searches for gamma-ray signatures of light dark matter for nearby dwarf galaxies.

Strongest magnetic fields: *Identify high-energy radiation processes through polarization measurements and study instabilities of magnetospheres.* GRIPS will detect 30-40 pulsars in the 0.2-80 MeV energy range, based on the Fermi pulsar catalogue extrapolated to lower energies, as well as extrapolation to higher energies of the hard spectra of the youngest pulsars detected by INTEGRAL and RXTE/HEXTE at hard X-ray energies. Most of the latter pulsars appear to reach their maximum luminosity in the MeV regime. GRIPS-determined light-curves and phase-resolved spectra will provide decisive constraints on the HE-emission geometry in pulsar magnetosphere and the acceleration processes located therein. For brighter pulsars, polarisation data will identify the nature of the emission. Measurements of pulsar wind nebulae (prominent examples at MeV energies are the Crab nebula and Vela X-1) will track the outflow of relativistic particles and fields. GRIPS will search for photon splitting in strong B-fields in selected pulsars and AXPs/SGRs. Splitting suppresses the creation of pairs, and inhibits escape of any near-surface emission above about 10-20 MeV.

4. Outlook

For the communities of high-energy astrophysics, cosmic ray physics, and astroparticle physics, GRIPS could become an important next-generation observatory. The many open questions about cosmic particle accelerators and the final states of stellar evolution will find their answer only in the transition regime from the thermal to non-thermal plasma at the threshold for electron-positron pair production, and with the help of the ultimate diagnostics of nuclear lines. Implementing GRIPS in the frame of a multi-frequency observatory which includes a detector for high-energy gamma rays such as Gamma-400 [11] seems to be a viable option for the future with bright scientific prospects.

References

[1] Schönfelder, V. et al., Astron. Astrophys. Suppl. **143**, 145 (2000)

[2] Krivonos, R., Tsygankov, S., Revnivtsev, M., Grebenev, S., Churazov, E., Sunyaev, R., Astron & Astrophys. **523**, 61 (2010)

[3] Beckmann, V., et al., Astron. & Astrophys. **505**, 417 (2009)

[4] Telezhinsky, I., Eckert, D., Savchenko, V., Neronov, A., Produit, N., Courvoisier, T.J.-L., Astron. & Astrophys. **522**, 68 (2010)

[5] Diehl, R., Lang, M., Kretschmer, K., and Wang, W., NewAR **52**, 440 (2008)

[6] Kanbach, G., et al., NIMPA **541**, 310 (2005)

[7] Greiner, J. et al., Experimental Astronomy **23**, 91 (2009)

[8] Zoglauer, A., et al., SPIE **7011**, 101 (2008)

[9] Iyudin, A.F., Galkin, V.I., Dzhatdoev, T.A., Astron. Rep. **53**, 102 (2009)

[10] Ajello, M., et al., Astrophys. J. **699**, 603 (2009)

[11] Ginzburg, V.L., et al., Cosmic Research **45**, 449 (2007)

PoS(Texas 2010)249