Abstract The primary scientific goal of the GRIPS mission is to revolutionize our understanding of the early universe using $\gamma$-ray bursts. We propose a new generation gamma-ray observatory capable of unprecedented spectroscopy over a wide range of $\gamma$-ray energies (200 keV–50 MeV) and of polarimetry (200–1000 keV). Secondary goals achievable by this mission include direct measurements of supernova interiors through $\gamma$-rays from radioactive decays, nuclear astrophysics with massive stars and novae, and studies of particle acceleration near compact stars, interstellar shocks, and clusters of galaxies.

Keywords Compton and Pair creation telescope, Gamma-ray bursts, Nucleosynthesis, Early Universe

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1 Introduction: Stepping beyond classical limits

Gamma-ray bursts (GRB) are the most luminous sources in the sky, and thus act as signposts throughout the Universe. The long-duration sub-group is produced by the explosion of massive stars, while...
short-duration GRBs likely originate during the merging of compact objects. Both types are intense neutrino sources, and being stellar sized objects at cosmological scales, they connect different branches of research and thus have a broad impact on present-day astrophysics.

Identifying objects at redshift $z \gtrsim 6.5$ has become one of the main goals of modern observational cosmology, but turned out to be difficult. GRBs offer a promising opportunity to identify high-redshift objects, and moreover even allow us to investigate the host galaxies at these redshifts. GRBs are a factor $10^5 - 7$ brighter than quasars during the first hour after explosion, and a favourable relativistic $k$-correction implies that they do not get fainter beyond $z \sim 3$. Yet, present and near-future ground- and space-based sensitivity limits the measurement of redshifts at $z \sim 13$ (as $H$-band drop-outs), because GRB afterglows above $2.5 \mu m$ are too faint by many magnitudes for 8–10 m telescopes. Thus, a completely different strategy is needed to step beyond redshift 13 to measure when the first stars formed.

Fortunately, nuclear physics offers such a new strategy. Similar to X-ray and optical absorption lines due to transitions between electronic levels, resonant absorption processes in the nuclei exist which leave narrow absorption lines in the $\gamma$-ray range. The most prominent and astrophysically relevant are the nuclear excitation and Pygmy resonances (element-specific narrow lines between 5–9 MeV), the Giant Dipole resonance (GDR; proton versus neutron fluid oscillations; $\sim 25$ MeV; two nucleons and more) and the Delta-resonance (individual-nucleon excitations, 325 MeV; all nucleons, including H!). Such resonant absorption only depends on the presence of the nucleonic species, and not on ionization state and isotope ratio. They imprint well-defined spectral features in the otherwise featureless continuum spectra of GRBs (and other sources). This is completely new territory (Iyudin et al. 2005), but with the great promise to measure redshifts directly from the gamma-ray spectrum, i.e. without the need for optical/NIR identification!

Technically, this new strategy requires sensitive spectroscopy in the 0.2–50 MeV band. The detection of GRBs requires a large field of view. Therefore, the logical detection principle is a Compton telescope. In addition, such detectors can be tailored to have a high polarisation sensitivity. Polarimetry is the last property of high-energy electromagnetic radiation which has not been utilized in its full extent, and promises to uniquely determine the emission processes in GRBs, as well as many other astrophysical sources. With its large field of view, such a detector will not only scan 80% of the sky within one satellite orbital period of 96 min., but also provide enormous grasp for measuring the diffuse emission of nucleosynthesis products and cosmic-ray acceleration.

2 Scientific Goals

2.1 Main mission goal

We aim at a detection of gamma-ray bursts at redshifts above 13. This will allow us to explore rather directly the universe in the epoch where first stars formed.

2.1.1 When did the first stars form?

High-redshift GRBs: GRB afterglows are bright enough to be used as pathfinders to the very early universe. Since long-duration GRBs are related to the death of massive stars, it is likely that high-redshift GRBs exist. Theoretical predictions range from few up to 50% of all GRBs being at $z > 5$ (Lamb & Reichart 2001, Bromm & Loeb 2002), and stellar evolution models suggest that 50% of all GRBs occur at $z > 4$ (Yoon et al. 2006). The polarisation data of the Wilkinson Microwave Anisotropy Probe (WMAP) indicate a high electron scattering optical depth, hinting that the first stars formed in the range $20 \lesssim z \lesssim 60$ (Kogut et al. 2003, Bromm & Loeb 2006, Naoz & Bromberg 2007). GRIPS is designed to measure GRBs from the death of these first stars and probe the universe up to the highest redshifts after matter-photon decoupling.

Redshift determination via resonance absorption: The observational use of nuclear resonance absorption for GRB redshift determination depends on two critical questions: “Is there enough matter along the sight lines to GRBs?”, and “Is the resulting absorption detectable?”. Is there enough matter along the sight lines to GRBs? Apart from galactic foreground extinction, relatively little intrinsic extinction has been found in the afterglow spectal energy distributions of GRBs, both at X-rays and at optical/NIR wavelengths. A recent combined analysis of Swift XRT
and UVOT data shows that the absorbers associated with the GRB host galaxy have column densities (assuming solar abundances) ranging from $(1-8) \times 10^{21}$ cm$^{-2}$ (Schady et al. 2007). Yet, there is evidence, both theoretical as well as observational, that there is substantial amount of matter along the line of sights to GRBs. This applies to the local GRB surrounding as well as to the larger environment of the host galaxy in which the GRB explodes. Temporally variable optical absorptions lines of fine-structure transitions indicate that (i) all material at distances within a few kpc is ionized, most likely by the strong UV photon flux accompanied with the emission front of the GRB, and (ii) beyond this ionized region the absorbing column is still at a level of $10^{21}$ cm$^{-2}$ (Vreeswijk et al. 2007). Thus, present-day measurement capabilities in the optical/NIR as well as X-rays are not adequate to determine the density of local matter around GRBs. However, at $\gamma$-rays this matter will be measurable through nuclear resonance absorption even though this matter is simultaneously being ionized: the GRB gamma-ray radiation has to pass through it - and it will suffer resonance absorption independent on whether this material is ionized or not.

A variety of theoretical simulations of GRB progenitors have been made (e.g. Bate & Bonnell 2003, Yoshida et al. 2006, Abel et al. 2007, Gao et al. 2007), pertaining to the formation of the first stars, the fragmentation rate, and density structure around the first star. The first stars are thought to form inside halos of mass $10^5...10^6 M_\odot$ at redshifts 10-60. It is generally accepted that most of the $10^5...10^6 M_\odot$ halo mass remains in the surroundings of the forming protostar, with about the original dimensions of the proto-cloud. The resulting mass of the star as well as the density structure are difficult to predict because they depend on the collapse conditions (merger or not, strength of winds, etc). However, it is important to realize that some simulations in fact predict column densities of up to $10^{29}$ cm$^{-2}$ around the first stars (Yoshida et al. 2006, Spolyar et al. 2008; see also Fig. 1)! These simulations have been done independent of the knowledge of nuclear resonance absorption. It remains to be demonstrated (preferentially observationally) whether the conditions modelled in these simulations are realized. Yet, the existence of what one “normally” would refer to as “unbelievably high” column densities is plausible – note that even pristine and fully-ionized hydrogen imprints resonant absorption! GRBs are the best and possibly only tool to measure such conditions.

Is the resulting absorption detectable? This question can be subdivided into two issues: Firstly, are there astrophysical conditions which favour large line of sight columns, but not excessively large densities? If the density is too high, multiple-scattering of higher energy photons could partly fill the energy window of a resonance, thus smearing the absorption trough. This may happen via Compton scattering or the cascading of high-energy photons. While the total pair production or Compton scattering cross sections are about a factor of 30-40 larger than the peak cross section of the Giant Dipole or Delta Resonance, the jet geometry in both, GRBs as well as blazars, over-compensates for this statistical measure: it is the differential cross section which matters. At the Dipole Resonance energy, the Compton-scattered photon beam has a full-width-half-maximum of $16^\circ$, or 0.5 sr. For a $1^\circ$ opening angle of the jet, the resulting GDR absorption is a factor $\sim 12$ more efficient than the Compton re-scattering of higher energy continuum photons into the beam. In addition, Compton scattering changes the energy of the scattered photon by arbitrary large values, much greater than the width of the resonance - this adds another factor of $E/\Delta E$ ($\geq 3$ for the GDR) in favor of the resonance absorption. For pair production, only the latter effect comes into play. Furthermore, even in high-density environments, there are two
Fig. 2 Left: 3C 279 spectrum during the January 1996 flare as measured by COMPTEL (diamonds) and EGRET (squares), which includes the $\Delta$ resonance absorption in the circumnuclear environment (red line) in addition to a cut-off power law (black line). The best-fit energy for the $\Delta$ resonance is $208 \pm 25$ MeV, implying a redshift $0.57 \pm 0.12$, close to the optically determined $z=0.536$. Right: Fit to the combined COMPTEL/EGRET spectrum of GRB 930131. The throughs at 5-8 MeV and 100-200 MeV are compatible with the Giant Dipole and Delta resonance, respectively, at a redshift of $z\sim 1$ (Iyudin et al. 2007b).

possibilities which alleviate the problem of re-filling: (i) the transverse dimension of the absorber is less than $\sim 1.5$ attenuation lengths at the energy of the highest attenuation value (Varier et al. 1986) or (ii) the absorber consists of many clumps (clouds) of matter, a solution which has been proposed to explain the UV and X-ray (Arav et al. 2003; 2005) or IR emission (Elitzur et al. 2004) in optically thick absorbers around AGN. First hints for resonance absorption in AGN (Fig. 2 left panel; Iyudin et al. 2005), and GRBs (Fig. 2 right panel) at the $2\sigma$ level have been found based on COMPTEL and EGRET data.

Secondly, how narrow/broad will the resonant absorption features be at different redshifts, and what is the required energy resolution and sensitivity to detect them? Fig. 3 shows the rest-frame resonance absorption lines for two different metallicities which clearly illustrate their starkly different relative intensity ratios. The GDR around 25 MeV has a FWHM $\sim 10$ MeV, thus GRIPS' $\sim 300$ keV resolution at 10 MeV is fully sufficient to properly resolve the feature. The goal of GRIPS is to measure those resonance absorptions at redshifts $z \sim 13-30$. A simulated GRB spectrum at $z=25$ is also shown in Fig. 3. Full simulations for the $\gamma$-ray instrument on GRIPS show that column densities of $10^{26} \ldots 10^{27}$ cm$^{-2}$ will be detectable for $\sim 30\%$ of all GRBs seen in spectroscopy mode, and those with as little as $10^{25}$ cm$^{-2}$ for the $10\%$ brightest GRBs (see sect. 4.2.4).

These features have not been seen before in EGRET TASC, BATSE SD, or COMPTEL (D2) data due to the combination of insufficient sensitivity, poor energy resolution and pre-canned response matrices for fixed energy bins. GRIPS will move $\gamma$-ray astronomy into a new era combining sensitivity,
2.1.1 GRIBS: A new instrument for GRB study

GRIPS observes the GRB environment with a multi-angle detector system and high energy resolution. It is designed to be compact and lightweight, facilitating its deployment in various locations. The instrument's sensitivity and versatility make it a valuable tool for future GRB studies.

2.1.2 What are the energetics of GRBs?

There is increasing evidence, both observational (Starling et al. 2005) and from theory (Woosley et al. 2006) that a GRB may launch two jets: one highly relativistic ($\Gamma > 200$, kinetic energy of $10^{51}$ erg), central jet with an opening angle of a few degrees, and a broader jet with sub-relativistic ejecta ($0.1c$, kinetic energy $10^{52}$ erg) spread over 1 radian. The underlying physical basis of the correlation between the isotropic equivalent energy emitted in the prompt radiation phase and the peak energy ($E_{\text{peak}}$) of the measured spectrum (Amati et al. 2002, Ghirlanda et al. 2004) is mysterious. Measuring the Lorentz factor $\Gamma$ from the $\gamma$-ray emission itself with GRIPS would provide a major step in understanding the cause of this correlation and in determining the energetics of GRBs.

Numerical models of the prompt emission due to internal shocks in an expanding relativistic wind exist in many different variants. In most of these, the spectrum is expected to significantly deviate from an optically thin synchrotron spectrum. A time-dependent calculation which includes cyclotron emission and absorption, inverse and direct Compton scattering, and $e^+e^-$ pair production and annihilation has shown (Pe`er & Waxman 2004) that (i) (in-flight) annihilation emission lines are expected at surprising strength (Fig. 4), and (ii) thermal Comptonization leads to emission peaking at $\sim 30$ MeV, possibly explaining the additional MeV component seen in GRB 941017 (Gonz´alez et al. 2003). The annihilation line will be boosted by $\Gamma$ into the $\sim 100$ MeV range, but adiabatic energy losses as well as GRB cosmological redshift lowers the observed photon energy back into the few MeV band. Thus, once the redshift is determined by the resonance lines (or ground-based optical/NIR telescopes for $z<13$), the measured energy of the annihilation line allows a direct determination of the Lorentz factor from the prompt $\gamma$-ray burst emission spectrum. GRIPS will allow us to measure the Lorentz factor of the prompt $\gamma$-ray burst emission via the predicted annihilation line, and thus directly measure the total energy of the explosion for at least 15% of all GRBs. Since the measured annihilation line energy is proportional to the ratio $\Gamma/z$, GRIPS can detect the line in the range $(0.5 \gtrsim \Gamma/(1+z) \gtrsim 100)$, thus covering the full predicted range of $\Gamma$ (50–1000) and $z$ (0.5-60).

2.1.3 What is the emission mechanism?

Spectra: Based on the knowledge gained from observation in the keV-MeV range several possible radiation mechanisms exist, all of which produce characteristic spectra in the super-MeV range. Two main classes of models (see Mészáros 2006) have been discussed. (1) Synchrotron/inverse Compton emission of electrons and protons: It is very probable that particles are accelerated to very high energies close to the emission site. This could either be in shock waves, where the Fermi mechanisms or other plasma instabilities act, or in magnetic reconnection sites. Therefore, it is likely that the...
observed emission in the keV range scatters on these relativistic electrons, which will result in inverse Compton emission in the super-MeV domain. This occurs in both internal and external shock scenarios. Furthermore, most of the outflow energy, transported by the protons will predominantly be in the super-MeV range. (2) Hadron related emission via pion production and cascades: High-energy, neutral pions (π⁰) can be created as shock-accelerated, relativistic protons scatter inelastically off ambient photons (pγ interactions). These later decay into γ-rays. This is, e.g., suggested to occur in GRB 941017 (González et al. 2003). Similarly, if the neutrons in the outflow decouple from protons, inelastic collisions between neutrons and protons can produce pions and subsequent high-energy emission.

The spectra of some GRBs alternatively have been well fit by both the Band model and a combination of a black body plus power law model (McBreen et al. 2006, Ryde et al. 2005). Rees (2005) suggested that the $E_{\text{peak}}$ in the γ-ray spectrum is due to a Comptonised thermal component from the photosphere, where the comoving optical depth falls to unity. The thermal emission from a laminar jet when viewed head–on would give rise to a thermal spectrum peaking in the X-ray or γ-ray band. The resulting spectrum would be the superposition of the Comptonised thermal component and the power law from synchrotron emission. Thus, from theory there is no indication that GRB spectra should deviate from a smooth continuum, and thus can be used as reliable background light sources for nuclear absorption features.

GRIPS will measure the broad-band spectra of $\sim$660 GRBs/yr from 100 keV – 50 MeV with 3% energy resolution. GRIPS will distinguish between the various, contradictory mechanisms by covering the transition from the classical keV and the dozen MeV regime.

**Polarisation as a diagnostic of the GRB emission mechanism:** The link between the γ-ray production mechanism in GRBs and the degree of linear polarisation can constrain models. A significant level of polarisation can be produced in GRBs by either synchrotron emission or by inverse Compton scattering. The fractional polarisation produced by synchrotron emission in a perfectly aligned magnetic field can be as high as 70–75%. An ordered magnetic field of this type would not be produced in shocks but could be advected from the central engine (Granot & Königl 2003, Granot 2003, Lyutikov et al. 2003). It should be possible to distinguish between Synchrotron radiation from an ordered magnetic field advected from the central engine and Compton Drag. Only a small fraction of GRBs should be highly polarised from Compton Drag because they have narrower jets, whereas the synchrotron radiation from an ordered magnetic field should be a general feature of all GRBs.

GRIPS will allow us to measure the polarisation of the prompt γ-ray burst emission to a few percent accuracy for about 10% of all detected GRBs. Moreover, the superior polarisation sensitivity will even securely measure whether or not the percentage polarisation varies with energy, angle and/or time over the burst duration of a dozen brightest GRBs.

### 2.2 Other mission goals

GRIPS will address other, non-GRB science topics, and lead to guaranteed science returns. Major science topics are (a) to unveil the physics of stellar explosions, and (b) to illuminate the physical processes which lead to particle accelerators from thermal up to relativistic (cosmic-ray) energies.

With the imminent launch of NASA’s GLAST Observatory (30 MeV - 100 GeV) and the long-term continuation of ESA’s INTEGRAL Observatory (20 keV - few MeV) there will be a dramatic lack of coverage of the gamma-ray sky in the 1-30 MeV range. GLAST will detect thousands of new sources, while the only existing MeV data (from GRO/COMPTEL) is for a handful of very bright ones. The discovery potential is clearly enormous. At present, multiwavelength spectra of the majority of sources have a notable absence of data at MeV energies, although often the main power is expected there. Without a mission like GRIPS, the MeV sky with its wealth of astrophysics will be less well known even than the TeV sky (via the new Cerenkov observatories), which is a quite disillusioning prospect.

#### 2.2.1 Nuclear astrophysics

**Supernovae of Type Ia** (SNIa) are considered on purely empirical grounds to be standardizable candles; no physical explanation could be established for the homogeneity of thermonuclear disruptions of white dwarf stars, which is the widely-accepted model. In view of the far-reaching cosmological implications of the apparent dimming of SNIa in the distant universe, this remains a major concern.
for supernova scientists (Leibundgut 2001, Branch & Nomoto 2007). Phrased at an extreme: dark energy might not exist at all, if our estimates of SNIa properties across cosmic times or selection biases are inadequate! Already a 7% Ibc contamination level is sufficient to produce $\Omega_\Lambda = 0.7$ from no effect (Homeier 2005). Thus, understanding the physics of SNIa is of utmost importance. GRIPS will provide the data for a physical understanding of the Phillips relation and the related errors. Due to the huge dynamic scales in time and space of the relevant physical processes, numerical simulations must make use of approximations. Guidance from observations is essential in building a physical model. Most direct access to isotope information would be through nuclear lines emitted from radioactive decays, which even can provide kinematic information from partially-embedded freshly-synthesized species. Penetrating $\gamma$-rays are expected to escape from the supernova as early as a few days after the explosion. $^{56}$Ni decays to $^{56}$Co within $\sim$8 days, which then decays to stable $^{56}$Fe within $\sim$111 days, producing $\gamma$-ray lines at 158 keV ($^{56}$Ni, early and probably occulted) and at 847, 1238, 1771 and 2598 keV. Line shape and centroids reflect the original $^{56}$Ni kinematics, line ratios are a key diagnostic of the explosion morphology and hence model types. In the period before full $\gamma$-ray transparency is reached ($\sim$100 days), $\gamma$-rays from $^{56}$Co decay provide the key information; the GRIPS band is designed to include these lines. Recent SNIa surveys record $\sim$10 nearby events ($<50$ Mpc; Isern, priv.comm.), which will be detected by GRIPS in the energy range of the (direct and scattered) $^{56}$Ni decay $\gamma$-ray range up to $\sim$2.5 MeV at $\sim$100 days after explosion, when the SN is transparent to gamma-rays (see Sim & Mazzali 2008). In addition to an absolute determination of the $^{56}$Ni amount from the $\gamma$-ray line flux, due to its broad energy range, line ratio diagnostics will be provided by GRIPS, thus significantly enhancing the sample of SNIa with meaningful $\gamma$-ray constraints.

GRIPS will at least measure one SNIa per year in one or more of the $^{56}$Ni decay gamma-ray lines, to constrain explosion models through energy-dependent transparency and the absolute $^{56}$Ni radioactivity.

Massive-star nucleosynthesis is responsible for most of the intermediate-mass elements from oxygen through iron (Woosley & Weaver 1995; Heger et al. 2003). Different burning episodes from hydrogen through silicon burning in shells of the rapidly-evolving star after its core-hydrogen burning phase (main sequence), plus nucleosynthesis in the supernova following the final gravitational collapse of the star, are responsible for this element production. The complexities of stellar-structure evolution and active nuclear-reaction networks are difficult to model. Beyond the (precise and abundant, but rather indirect) observations of elemental abundances through atomic lines, measurements of the key isotopes through their radioactive decays provide calibrators of those models.

A key isotope for supernova-interior nucleosynthesis is $^{44}$Ti with a decay time of $\sim$85 years, a $\gamma$-ray line at 1156 keV and X-ray lines at 68 and 78 keV. This radioactive decay has been observed from the Cas A supernova remnant (Iyudin et al. 1994, Vink et al. 2001). Its abundance and kinematics directly arises from the processes of accretion and fall-back onto the central remnant. This otherwise unaccessible inner region of a core collapse is at the origin of gamma-ray burst formation by massive stars (The et al. 2006). GRIPS will deepen surveys for $^{44}$Ti gamma-ray sources (1.16 MeV) in the Galaxy within a 5-year mission down to $6\times10^{-7}$ ph cm$^{-2}$ s$^{-1}$, and should detect 10-15 sources if $^{44}$Ti ejection is typical for core-collapse supernovae (see The et al. 2006). Furthermore, detection of MeV
continuum in core-collapse SNe, and especially in the Ib/c class, would indicate that a fraction of the relevant kinetic energies liberated in these explosions is conveyed to the acceleration of electrons to very high energies and to the re-emission through the synchrotron process, illuminating our understanding of the GRB-powering mechanisms in SNe. Moreover, if the high energy spectrum were polarized, we would get unique insights into the geometry of the magnetic fields. For a sufficiently closeby (less than 100 Mpc) SN associated with a GRB, prompt gamma-ray spectroscopy of possible early $^{56}\text{Ni}$ lines at 158 keV and 812 keV would be another unique opportunity, according to the predicted gamma-ray flux near the time of transparency ($\sim$50-100 days) (see Sim & Mazzali 2008). GRIPS would be the only monitor for such continuum and radioactivity MeV gamma-rays from nearby core-collapse supernovae, with these unique signatures.

The $^{60}\text{Fe}$ isotope is produced in late burning stages of massive stars, and only ejected by the terminal supernova. $^{60}\text{Fe}$ decays with $\sim$2.2 My, hence cumulative production over My time scales is observed in the $\gamma$-ray lines. INTEGRAL detected the $\gamma$-ray lines from this isotope in the larger region of the inner Galaxy (Wang et al. 2007). Yet, spatial information is insufficient to be able to conclude on an origin from core collapse SN. With a 5-year survey sensitivity of $\sim$6×10$^{-7}$ ph cm$^{-2}$ s$^{-1}$, GRIPS will map the Galaxy in $^{60}\text{Fe}$ radioactivity gamma-rays for the first time at several degrees spatial resolution. This will allow detailed tests of massive-star nucleosynthesis models for massive-star regions of different ages along the plane of the Galaxy.

The $^{26}\text{Al}$ isotope is predominantly produced by massive stars (Prantzos & Diehl 1996), although not only by supernovae, but with nucleosynthesis in early stages of core hydrogen burning and in late shell burning stages plus supernova nucleosynthesis (Limongi & Chieffi 2006). With a 1.04 My decay time, its cumulative emission in the 1808.65 keV $\gamma$-ray line provides a diagnostic of massive-star nucleosynthesis in the Galaxy (Diehl et al. 2006). The $^{26}\text{Al}$ production in nearby massive-star clusters with correspondingly-low surface brightness are within reach with the sensitivity of GRIPS. This is a key ingredient of chemical-evolution models of galaxies (MacLow & Klessen 2004). GRIPS will deepen the Galactic surveys for these key isotopes of massive-star nucleosynthesis, and provide significant improvement on the Galactic distribution of massive-star radioactivities.

**Novae** are understood as explosive Hydrogen burning on the surface of a white dwarf (WD), igniting once a sufficient amount of matter has been accreted from the WD’s companion star. Nuclear burning is dominated by rapid proton capture (rp-process) on light elements, and the main theoretical issue is up to which heavy isotopes the rp-process proceeds. Many proton-rich isotopes are produced, which undergo $\beta^+$-decay at their characteristic decay times, most important contributions being from $^{13}\text{N}$ ($\tau \sim$14 min) and $^{18}\text{F}$ ($\tau \sim$2.5 h) (Hernanz et al. 2002, Hernanz & Jose 2006). Therefore, a bright flash of positron annihilation emission with a characteristic line at 511 keV and a bright lower-energy continuum occurs right after the thermonuclear runaway, well before the envelope expands and lights up as a nova in optical emission. Alongside the rp-process, radioactive $^7\text{Be}$ is produced and is expected to be the brightest $\gamma$-ray line source, with a decay time of 78 days ($E_\gamma$ = 478 keV).

GRIPS will detect several Galactic novae through annihilation emission, and combine positron annihilation with $^7\text{Be}$ and $^{22}\text{Na}$ diagnostics to understand the nova ignition and burning process.

### 2.2.2 Positron Astrophysics

Imaging of the $\gamma$-ray emission from the annihilation of positrons with INTEGRAL/SPI (Knödlseder et al. 2005) has revealed a new major puzzle: The expected sources of positrons in the Galaxy are predominantly located in the disk of the Galaxy, while the Galactic bulge is by far the brightest observed feature in annihilation $\gamma$-rays. This initiated a quest for new types of candidate positron producers, such as the annihilation of dark matter particles accumulated by the Galaxy’s gravitational field (Hooper & Wang 2004). An alternative hypothesis could be the large-scale transport of positrons from their disk sources through the Galactic halo into the central bulge before their annihilation (Prantzos 2004), or significant diffusion of positrons generated by past activity and energetic proton ejection from the central black hole in our Galaxy (Cheng et al. 2006).

GRIPS will help to clarify the validity of such extreme models, as it will be sensitive to the full spectral range of annihilation emission (300–511 keV, and above, for annihilations-in-flight). With its angular resolution of $\sim$3.5 at 511 keV, GRIPS will map the bright bulge emission of positron annihilation and its merging with the disk component; the latter can be mapped with GRIPS along the bright regions of the disk such as the inner ridge and Cygnus, as inferred from $^{26}\text{Al}$ gamma-rays and its associated positron production (see Zoglauer et al. 2008).
2.2.3 Other γ-ray sources

Blazars: Recent Swift/BAT observations find many blazars with very flat (photon index 1.6–1.8) spectra in the 20–150 keV range, and extrapolations indicate that all of those will be securely detectable by GRIPS. The measurement of the resonance absorption will substantially help in the identification process, since the redshift will be known from the gamma-ray spectra (Iyudin et al. 2005, 2007a). Gamma-ray polarization can be measured for the flare states. Comparing with radio polarization and multi-wavelength light-curves, this will pin down the origin of the γ-ray flares (Wehrle et al. 2001; Jorstad et al. 2006).

Pulsars, AXPs, and SGRs: Pulsars are an excellent laboratory for the study of particle acceleration, radiation processes and fundamental physics in environments characterized by strong gravity, strong magnetic fields, high densities and relativity. Above ∼ 50 MeV EGRET has detected 6-10 pulsars and candidates (Thompson et al. 1999) and Schönfelder et al. (2000) reported for the COMPTEL survey 4-5 pulsars corresponding to EGRET detections and one high-magnetic field pulsar (PSR B1509-58) with emission up to 30 MeV. Estimates for the number of possible pulsar detections by future, more sensitive, gamma-ray instruments are based on our empirical knowledge of pulsar efficiencies and spectra, new radio surveys that now contain about 2000 pulsar detections, and on the extrapolations afforded by theories of high-energy emission from rotating, magnetized neutron stars. These theories are still quite disparate. For energies above several 10 MeV and for the sensitivity of the Large Area Telescope on GLAST, predictions range from ∼ 60 detections (Harding et al. 2007) to about 500 (Jiang & Zhang 2006), with several predictions between 120 and 260 pulsars. Many of these pulsars are so-called ‘radio-quiet’ objects comparable to the Geminga pulsar. Additional predictions for about 100 millisecond-pulsars have been published for GLAST by Story et al. (2007). GRIPS’ sensitivity for wide band spectra above ∼ 10 MeV (normal pulsars) and below 1 MeV (high B-field pulsars and AXPs) exceeds the COMPTEL sensitivity by a similar factor that holds when going from EGRET to GLAST. From the EGRET/COMPTEL relation we therefore estimate the number of GRIPS pulsars to be about 50-70% of the GLAST pulsars and expect to detect 50-70 pulsars in the GRIPS energy range > 10 MeV. GRIPS-determined light curves and phase-resolved spectra in the 1–50 MeV range will provide decisive insights into the pulsar magnetosphere and the acceleration processes located there. Polarisation is a unique characteristic of particles radiating in strong magnetic fields. Pulsars and their surrounding pulsar wind nebulae (PWN) are highly polarised. GRIPS will be sensitive enough to measure polarisation below a few MeV from several pulsars.

'Magnetars' appear to observers in the forms of ‘anomalous X-ray Pulsars’ (AXP) or, possibly related, ‘soft gamma-ray repeaters’ (SGR). Pulsed radiation with a thermal spectrum at soft X-rays (1–10 keV) and an extremely hard power-law up to nearly 1 MeV has been observed from 6-8 AXPs (Kuiper et al. 2006). The continuous all-sky survey of GRIPS promises to capture unique data for high-energy neutron star astrophysics.

Superbubbles: Massive stars in the Galaxy appear in groups (e.g. OB associations), such that their strong wind and supernova activity overlaps and generates large superbubbles (SBs). Interacting shocks within the superbubble thus provides a natural environment for cosmic ray acceleration (GCRs). GRIPS has sufficient sensitivity to test the theory of galactic cosmic ray acceleration in the SB environment by observing galactic SBs as well as 30 Dorado in the LMC in gamma-ray line emission. Lines of $^{12}\text{C}^*$ and of $^{16}\text{O}^*$ at 4.44 MeV, and 6.1 MeV, 6.97 MeV, and 7.17 MeV, respectively, would be the best indicators of the CR acceleration in the SB.

Diffuse continuum MeV gamma-ray emission from the interstellar medium arises from the interactions of cosmic-ray electrons with interstellar matter and radiation fields. Bremsstrahlung on atomic and molecular hydrogen produces gamma-rays with energies typically half of the electron energy, so that gamma-rays in the GRIPS range trace electrons in the 1-100 MeV ranges. At these energies direct cosmic-ray measurements are virtually impossible because of the large solar modulation; synchrotron radiation occurs at frequencies too low to be observable. Hence GRIPS gamma-ray observations are our only window to interstellar electrons at MeV energies. Inverse-Compton scattering of 100-1000 MeV electrons and positrons on interstellar radiation is an important component of continuum gamma-rays, and dominates at low energies. In fact, recently this component has been shown to explain most of the diffuse emission from the Galactic ridge observed by INTEGRAL (Porter et al. 2008). Both primary and secondary cosmic-ray electrons and positrons contribute to this emission, and hence observations in this part of the spectrum give valuable information on high-energy particles in the Galaxy. On the
other hand this process fails to explain all of the diffuse emission observed by COMPTEL (Strong et al. 2005, Porter et al. 2008), suggesting there could be a contribution from populations of unresolved hard gamma-ray sources, like AXPs and radio pulsars. GRIPS can trace and disentangle those components towards higher energies.

**Solar flares** accelerate ions to tens of GeV and electrons to tens of MeV. GRIPS would obtain high-statistics time-resolved spectra, permitting precise measurements of the hard-X ray continuum from accelerated electrons, of tens of strong nuclear lines and of the high-energy emission from π⁰ decay and π⁺-decay leptons. This, for the first time, would allow detailed studies of the evolution of the energy spectra and composition of the accelerated particles which are the key properties for the understanding of the acceleration mechanism and the transport of energetic particles in solar flares. In particular, it will be possible to determine the accelerated ³⁷He/⁴He ratio and the heavy-ion content of the interacting particles and compare them with observations of solar energetic particles in interplanetary space, where large overabundances of ³⁷He (≈ 100 - 1000) and of low-FIP elements (≈ 10-30) are found after impulsive-type flares. Additional information would come from polarization measurements of the bremsstrahlung continuum and of some nuclear lines and the detection of delayed X- and γ-ray line emission from solar active regions that are following the production of relatively long-lived radio-isotopes during strong flares (Tatischeff et al. 2006).

3 **Mission profile**

For the GRIPS mission, a mass of 3.5 t needs to be delivered to a circular equatorial low-Earth orbit (LEO), with an altitude of about 500 km. The Soyuz Fregat 2B is capable of launching this payload (capacity of 5.3 t) and with its fairing of diameter 3.8 m and height of 7.7 m readily accommodates GRIPS with the science instruments, the Gamma-Ray (GRM) and X-Ray Monitors (XRM).

GRIPS will generally be operated in a continuous zenith pointed scanning mode. The field of view (diameter 160°) will cover most of the sky over the course of one orbit. A similar strategy is planned for the all-sky survey of the high-energy telescope LAT on the forthcoming GLAST mission. Pointing the XRT to a selected source will not disturb the scanning coverage of the GRM, since the detector response is nearly invariant under rotation around the axis.

4 **Payload**

4.1 **Overview of instruments**

GRIPS will carry two major telescopes: the Gamma-Ray Monitor (GRM) and the X-Ray Monitor (XRM). The GRM is a combined Compton scattering and Pair creation telescope for the energy range 0.2–50 MeV. It will thus follow the successful concepts of imaging high-energy photons used in COMPTEL (0.7–30 MeV) and EGRET (>30 MeV) but combines them into one instrument. New detector technology and a design that is highly focused on the rejection of instrumental background will provide greatly improved capabilities. Over an extended energy range the sensitivity will be improved by at least an order of magnitude with respect to previous missions (Fig. ??) and the large field of view, better angular and spectroscopic resolution of GRM allows the scientific goals outlined in this project to be addressed. The XRM is based on the mature concept and components of the eROSITA X-ray telescope, which is scheduled for a space mission on the Russian platform Spektrum-XG (Predehl et al. 2006, Pavlinsky et al. 2006).

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