PROCEEDINGS OF SCIENCE

All-Sky Medium Energy Gamma-ray Observatory (AMEGO)

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The gamma-ray energy range from a few hundred keV to a few hundred MeV has remained largely unexplored since the pioneering but limited observations by COMPTEL on CGRO (1991-2000). Fundamental astrophysics questions can be addressed by a mission in the MeV range, from astrophysical jets and extreme physics of compact objects to a large population of unidentified objects.

To address these questions, we are developing AMEGO: **A**ll-sky **M**edium **E**nergy **G**amma-ray **O**bservatory, a NASA Probe class mission, to investigate the energy range from 300 keV to >10 GeV with good energy and angular resolution and with sensitivity approaching a factor of 20-50 better than previous instruments. Measurements at these energies are challenging, mainly due to the specifics of photon detection: Compton scattering and pair production compete. These two interaction processes require different approaches in both detection and data analysis, and consequently in the instrument concept. AMEGO will be capable of measuring both Compton-scattering events at lower energies and pair-production events at higher energies. Also, AMEGO will have sensitivity to linear polarization of detected radiation at a level of 20% minimum detectable polarization from a source 1% of the Crab, observed for 10^6 s. AMEGO will operate mainly in scanning (discovery) mode with field-of-view 2.5 sr (20% of the sky at any time).

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1.Introduction

The MeV domain is one of the most underexplored windows on the Universe. This has not resulted from a paucity of interesting science, but from technology constraints that have limited advances in detection sensitivity. Thanks to currently available technology, we can address this tantalizing gap in our knowledge of critical astrophysical questions. Known science that can be addressed at these energies is much too broad for any realizable single mission. Hence we focus on a large field of view instrument with good angular and energy resolution optimized for continuum sensitivity and some gamma-ray line and polarization capability. We have chosen to optimize our instrument in this energy range, to use both Compton scattering and pair production as detection techniques, for a compelling, high scientific return. Such a design can be achieved at reasonable cost with technologies that are currently in a high state of readiness.

Measurement at these energies is challenging. This is mainly due to it being a range where two processes of photon interaction, Compton scattering and pair production, compete, with a cros-sover at around 10 MeV depending on the material. These two interaction processes require dif-ferent approaches in both detection and data analysis, and consequently in the instrument con-cept. It is possible, though challenging, to design a cost-saving single instrument that will be able to use both kinds of photon interaction proces-ses and provide accurate results in the extended energy range from ~300 keV to above 10 GeV with continuum sensitivity a factor of >20 times deeper than COMPTEL in the overlapping energy range (**Fig.1 and Table 1**).

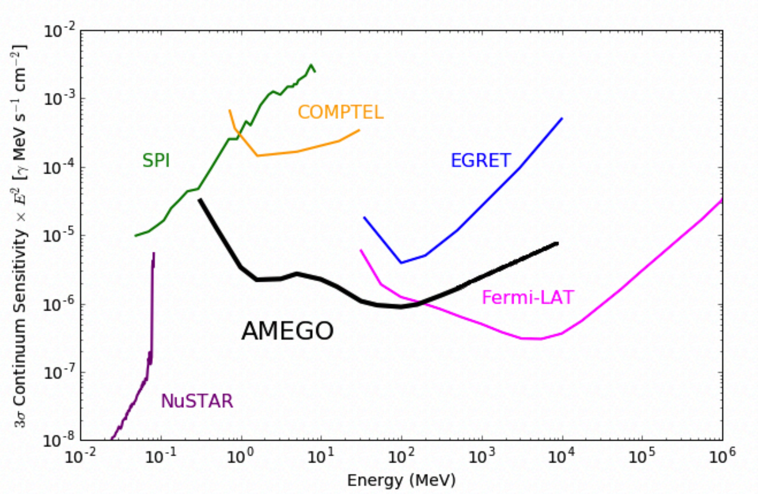

Figure 1. AMEGO continuum sensitivity (10^6 s) compared to other missions.

Energy Range	300 keV -> 10 GeV
Angular resolution	3° (3 MeV), 6° (10 MeV), 2° (100 MeV)
Energy resolution	<1% (< 2 MeV), 1-5% (2-100 MeV), ~10% (1 GeV)
Field of View	2.5 sr (20% of the sky)
Line sensitivity	<6×10^{-6} ph cm^{-2} s^{-1} for the 1.8 MeV ^{26}Al line in a 1-year scanning obser-vation
Polarization sensitivity	<20% MDP for a source 1% the Crab flux, observed for 10^6 s
Sensitivity (MeV s^{-1} cm^{-2})	3×10^{-6} (1 MeV), 2×10^{-6} (10 MeV), 8×10^{-7} (100 MeV)

Table 1. AMEGO Instrument Performance

2. Scientific objectives

We describe four among the many AMEGO scientific goals.

2.1 Use Astrophysical Jets to Probe the High-Redshift Universe

AMEGO will provide critical observations of the most massive black holes in the Universe, hosted at the centers of the brightest, most persistent, most powerful objects known, active galactic nuclei, or AGN [1a]. In an AGN, the central black hole mass can be up to a billion solar masses. Blazars, AGNs with powerful jets pointing towards the Earth, stand out for their extreme luminosities (10^{42} - 10^{48} erg s^{-1}) that originate in a relatively small volume. Blazars have two main emission mechanisms: accretion of material around the central black hole, by which the gravitational energy is extracted and partially converted into radiation; and ejection of material from the vicinity of the central object, through jets that accelerate particles to ultra-relativistic energies. The mechanisms are deeply coupled, with the majority of the observed energy often conveyed in the non-thermal, relativistic jets. The spectral energy distributions (SEDs) of blazars are typically characterized by double-humped structures, with a low-energy peak in the infrared-to-optical range, originating from synchrotron radiation of high-energy electrons, and a high-energy peak at gamma-ray energies whose origin is less well understood, coming from either energetic electrons or protons interacting with radiation, magnetic fields, and/or other particles, either close to the black hole or at some distance along the jet (**Fig. 2**). In many cases, the peak output is in the MeV band. **A majority of the blazars detected by Fermi LAT have power-law photon spectra steeper than E^{-2}, implying that their peak energy output lies below the LAT energy band, but in the AMEGO range.**

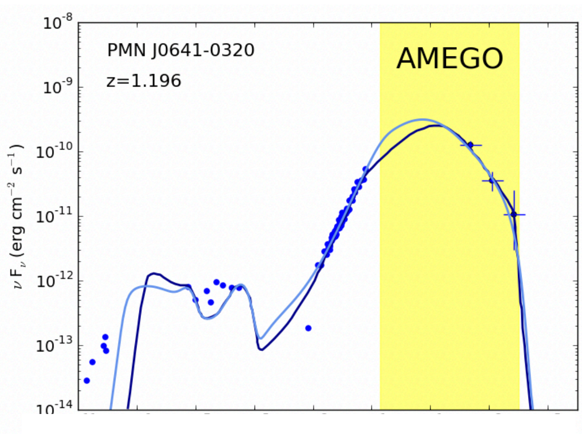

Figure 2 The spectral energy distribution (SED) of blazar PMN J0641 0320 [2] with energy output peaking in the MeV energy band, shows curves that represent different models for the location of the jet energy dissipation.

AMEGO will offer a unique view into blazars' emission mechanisms. Observations of the poorly explored 0.3–100 MeV energy band with AMEGO will measure their SEDs and variability with unprecedented sensitivity and link the observed characteristics to crucial physical parameters of these systems, such as the maximum energy to which particles are accelerated, the strength of the magnetic fields, the content of the jet, and the location of the gamma-ray emission site. The polarization measurement capability of AMEGO provides a crucial test of the jet content, because hadronic models predict a much higher degree of polarization than leptonic models.

Blazars with high-energy peaks in the MeV range have larger-than-average jet power and accretion luminosity and are often found at large redshift. Their number density grows quickly going back in time and is maximum at redshift around 4, which is more distant than for typical AGN and star-forming galaxies. Not surprisingly they harbor the most massive black holes, with masses $\geq 10^9\ M_\odot$. MeV blazars are thus powerful probes of the growth of supermassive black holes across the history of the Universe. At redshifts larger than 4, the time to grow a $10^9\ M_\odot$ black hole by accretion is similar to the age of the Universe, and as such this kind of system should be rare. Their detection implies that other black hole growth mechanisms, e.g., via direct collapse [3] must have occurred. The detection and characterization of the MeV blazar population is critical to understand black hole formation and growth at high redshift. Its ground-breaking sensitivity (**Fig. 1**) and all-sky survey capability ensure that AMEGO will measure the properties of a large sample of MeV blazars.

Models for Gamma-Ray Bursts (GRB) also have jet properties that can be distinguished by AMEGO. Short-duration (< 2 seconds) GRBs, whose jets are thought to be produced by neutron star-neutron star mergers, are prime candidates for gravitational wave detections by LIGO. AMEGO's sensitivity and field of view will enable detailed testing of merger models for counterparts of LIGO/Virgo and future gravitational wave observatory detections [1b].

2.2 Identify Extreme Conditions around Compact Objects

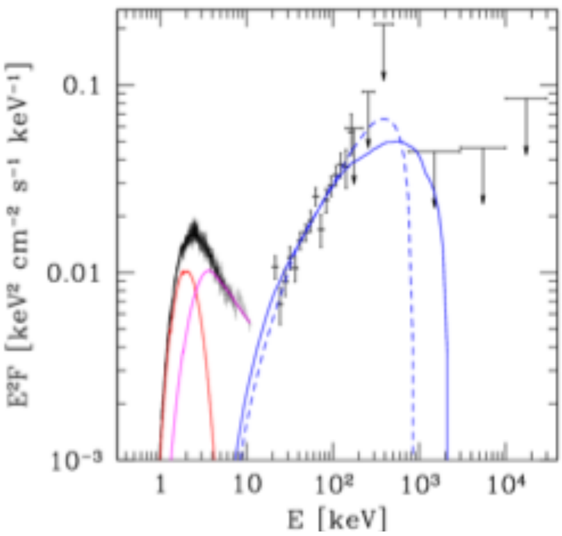

Figure 3. Spectral energy distribution of magnetar 1RXS J1708 4009 [5]. The solid blue and dashed blue lines show two different models for the shape of the high-energy cutoff.

AMEGO can resolve, important open questions about neutron stars. Neutron stars, with their extreme densities, electric potentials, and magnetic fields, display a great variety of observational characteristics and behavior (see [4], for a review). One of the intriguing puzzles is the connection between the rotation-powered pulsar (RPP) population and the magnetars, magnetically powered neutron stars that undergo violent bursting and whose quiescent emission far exceeds their spin-down luminosities. Many RPPs have surface dipole magnetic field strengths inferred from their period and period derivatives that are as high as those of magnetars, and some magnetars have dipole fields lower than many RPPs. What determines their very different behavior? Magnetar quiescent emission includes a hard component with spectra measured by INTEGRAL up to 200 keV and upper limits from COMPTEL and Fermi indicating a cutoff in the 1-10 MeV range (**Fig. 3**). On the other hand, many RPP spectra have non-thermal emission that extends to GeV energies. Recent observations of PSR J1119 6127, a radio, X-ray and gamma-ray RPP suggest a strong connection between magnetars and high-magnetic field pulsars and raise the possibility of a continuum between the two neutron star classes, but the nature is still unclear. Measurement of the phase-resolved quiescent spectra of magnetars with AMEGO will determine the high-energy cutoffs and assess how similar they are to the sub-GeV turnover seen in the high-field RPP PSR J1513-5908 [6]. They will also reveal whether the magnetic field has a significant toroidal component, thought to be a critical characteristic distinguishing magnetars and RPPs. Observation of high magnetic field RPPs following magnetar-like bursts could identify transient toroidal fields and answer the question of whether magnetic field structure distinguishes magnetar vs. RPP behavior.

The high-energy cutoffs in hard spectral components of magnetars are predicted to be highly polarized since pair production and photon splitting cutoffs occur at different energies and attenuate orthogonal emission modes [7]. The AMEGO measurements of this unique signature of near 100% polarization near the high-energy cutoff of magnetar quiescent spectra could verify that this emission comes from near the neutron star surface and provide an in situ measurement of a magnetar magnetic field.

Other topics: Unidentified MeV-peaked sources, known from Fermi LAT observations, represent guaranteed discovery opportunities. Neutrino sources are likely some type of compact object, and neutrino emission is closely related to gamma-ray production. Models of black hole binary systems, which have been seen to have polarized emission at lower energies by INTEGRAL, can be tested with the sensitivity and polarization capability of AMEGO.

2.3 Measure Synthesis of Elements in Dynamic Environments

The creation of "metals" in stars led to the enrichment of gas and stars in the Galaxy to a mass fraction of about 2%. This process of Galactic chemical evolution is driven by the star formation rate and the relative rates of various sources of nucleosynthesis occurring in dynamic environments; predominantly thermonuclear (Type Ia) and core-collapse (Type II) SNe. The chemical evolution processes are traced with spectroscopic abundance measurements in stars and the interstellar medium, where iron (mostly from SN Ia) and Oxygen (mostly from SNII) provide chemical clocks. Gamma-ray line astronomy contributes to this study in unique ways: for nearby SNe it is possible to directly measure the freshly synthesized amount of ^{56}Ni, the radioactivity for keeping supernovae (SNe) bright for much longer than the adiabatically cooling ejecta would allow. On longer time scales ^{44}Ti deposits energy on a 100 year time scale, and ^{26}Al and ^{60}Fe decay on a million year time scale. All these unique tracers of radioactivity produced in SNe reveal their presence via gamma-ray lines in the MeV band probed by AMEGO. The resulting diffuse gamma-ray line glow of these isotopes has been detected, and in fact allows us one of the best Galaxy-wide measurements of the Galactic star formation rate (averaged over a few million years).

Gamma-ray line observations furthermore offer an opportunity to probe the central regions of these explosive sites through the glow of SNe remnants that occurred in the past millennium, or the detection of SNe in the local universe. Particularly important is the potential to detect gamma-ray lines from nearby Type Ia supernova explosions [8]. AMEGO will detect ~15 SN Ia per year, out to a distance of at least 30 Mpc. The 847 keV line from ^{56}Co decay directly yields the ^{56}Ni mass, which AMEGO will measure precisely for the nearest SNIa events. This mass is a critical factor determining the SNIa light curves and their use as standardizable candles. Thus AMEGO will open a new window for testing SNIa calibration as distance indicators, and hence as probes of cosmic acceleration. With the boost of AMEGO's sensitivity relative to COMPTEL and INTEGRAL, the study of the radioactive galaxy will experience a renaissance. We expect to detect more remnants, better map the diffuse lines (including the puzzling 511 keV line), detect explosions in nearby galaxies, and finally detect the long predicted nuclear lines of CNO atoms excited by Galactic cosmic rays. AMEGO will study isotope production in ways only gamma rays can offer, where nuclear physics reigns and atomic sensitivities to the thermal state of the emitting plasma are minimized.

2.4 Test Models of Dark Matter

The era of precision cosmology revealed that 80% of the matter in the Universe is non-luminous, or dark. The nature of dark matter is crucial to our understanding of the structure and evolution of the Universe after the big bang. AMEGO will be the most sensitive probe in the MeV energy range to gamma-ray signatures of two leading dark matter candidates: Weakly Interacting Massive Particles (WIMPs) and axion-like particles (ALPs).

WIMP dark matter naturally arises in extensions of the Standard Model of particle physics. Typically WIMPs are thought to have masses > 1 GeV, which produce gamma rays with energies starting in the ~100 MeV range. This WIMP mass permits the production of gamma rays observable by the Fermi-LAT, which is sensitive to energies ranging from 20 MeV to >300 GeV. Although Fermi-LAT data have been used to perform many searches for WIMP dark matter, the broad point-spread function at low energies prevents sensitive dark matter searches below 500 MeV gamma-rays energy. AMEGO is ideal for searching for low-mass WIMP dark matter with the necessary precision in the MeV range for detection [1c].

ALPs interacting with photons in the presence of external magnetic fields lead to energy-dependent mixing similar to neutrino oscillations. These oscillations yield distinctive features in the energy spectra of the target observed. Ideal targets have known large magnetic fields, such as magnetars, blazars and galaxy clusters. Gamma rays from these sources often times traverse multiple magnetic-field environments in which gamma rays could convert into an ALP and vice versa. The resulting narrow-band features were recently searched for in the gamma-ray and X-ray spectra of NGC 1275 [9, 10], the central radio galaxy of the Perseus cluster. Its intrinsic brightness and the strong magnetic field of the cluster make this galaxy a prime target for ALP searches. AMEGO is, with its low energy threshold, large field of view, and excellent angular resolution, the perfect instrument to search for such a signal and will extend these searches to ALP masses by orders of magnitude. The sensitivity surpasses that of current and planned dedicated ALP laboratory searches.

3. Instrument Conceptual Design

To achieve the science described, we select an instrument design that enables continuum spectral measurements over a broad energy range with additional capabilities for measuring polarization and spectral lines. AMEGO will detect gamma rays via Compton scattering at low energies (< 10 MeV) and pair production at higher energies (> 10 MeV) as sketched in **Fig. 4.** In the Compton regime, the use of solid state technology and compact geometry provides substantial performance improvements relative to COMPTEL [11]. In the pair regime, AMEGO has been optimized for peak performance at lower energies [1d, 1e].

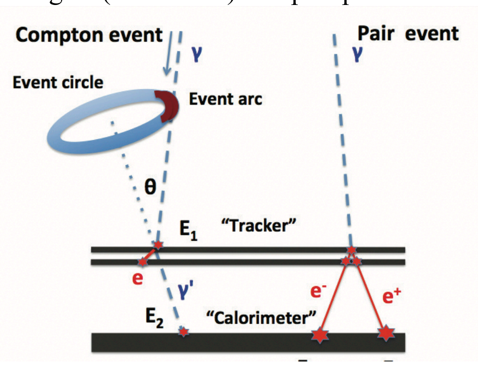

Figure 4. Event types for Compton-Gamma telescope

AMEGO consists of four subsystems: (**Fig. 5**) a double-sided silicon detector (DSSD) tracker, a segmented CdZnTe (CZT) calorimeter, a segmented CsI(Tl) calorimeter and a plastic scintillator anticoincidence detector (ACD). The CsI calorimeter and ACD are close analogs of systems flown on Fermi LAT [12]. The AMEGO concept is based on the engineering studies for ComPair[13] and the European-led MEGA [14] and GRIPS[15]. The AMEGO notional instrument performance is shown in Table 1.

The tracker converts or scatters incoming gamma rays and accurately measures the positions and energies of either the electron-positron pair or the Compton-scattered electron passing through the instrument. To improve low-energy performance relative to the LAT, passive conversion material between silicon detector layers has been removed and analog-digital conversion is included in the electronic readout. These enhancements improve the measurement of electron energy and therefore the resultant direction and energy of pair and Compton events. The tracker is divided into four modular towers, each consisting of 60 layers of DSSDs. The DSSDs are wire-bonded on the top and the bottom with x- and y-strips and read out on one x and y side. The layers are separated by 1.0 cm. This configuration was used to calculate the sensitivity curve shown in Fig. 1. Adjusting DSSD detector thickness, strip pitch and layer spacing results in trades between collection area, angular resolution, and field of view. The two calorimeter subsystems measure the final energy deposit of the events. The CZT calorimeter lies directly below the tracker and surrounds the lower tracker layers with a deeper CsI calorimeter below the CZT. The CZT calorimeter provides improved performance for Compton events, while the CsI calorimeter provides the depth to contain enough of a pair-conversion generated electromagnetic shower to extend the energy range to GeV energies.

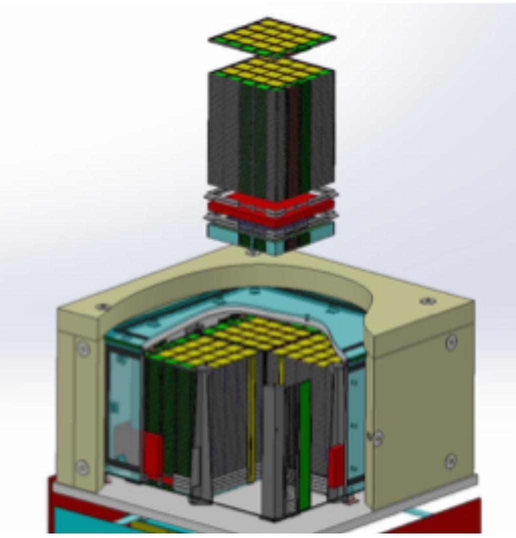

Figure 5. A mechanical sketch of AMEGO

The CZT calorimeter consists of an array of 8 mm x 8 mm x 40 mm bars. One layer sits below the tracker and another extends partially up the outer sides of the tracker [1f]. The CZT calorimeter provides a precise measurement of the location and energy of the scattered Compton photon, which is needed for event reconstruction. The side-wall layer boosts low-energy performance by enabling measurement of Compton events with large scattering angles. Polarization is determined from the azimuthal asymmetry of the scattered photon direction. The CZT bars are operated in a drift mode that enables 3-dimensional reconstruction of the location of the interaction in the detector, thus providing excellent positional resolution (< 1 mm) as well as very good energy resolution (< 1% at 662 keV) at room temperature.

The CsI calorimeter design is similar to the Fermi-LAT CsI calorimeter, but with dramatically improved low-energy performance by collecting the scintillation light with silicon photomultipliers. Each calorimeter module consists of 6 layers of CsI(Tl) crystal bars arranged hodoscopically.

The ACD is the first-level defense against the charged cosmic-ray background that outnumbers the gamma rays by 3–5 orders of magnitude. It covers the top and four sides of the tracker. The ACD utilizes the same plastic scintillator as used on the LAT with wavelength shifting (WLS) strips and a SiPM readout. WLS strips are inserted in grooves in each panel edge and viewed by two SiPMs, allowing more uniform light collection than with SiPMs alone.

4. Summary

The AMEGO concept builds on the strong heritage of the Fermi LAT and technology developed for gamma-ray and cosmic-ray detectors. Most components are at or above Technical Readiness Level 6. The design incorporates LAT technology with a few exceptions within an overall simpler structure. AMEGO will have the very broad science menu appropriate for a Probe class mission. As an all-sky surveyor it will collect data on all MeV sources in the sky and will provide a service to the whole astrophysical community

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