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ORIGINAL ARTICLE

A DUAL mission for nuclear astrophysics

The DUAL Consortium

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Abstract DUAL will study the origin and evolution of the elements and explores new frontiers of physics: extreme energies that drive powerful stellar explosions and accelerate particles to macroscopic energies; extreme densities that modify the laws of physics around the most compact objects known; and extreme fields that influence matter in a way that is unknown on Earth. The variability of these extreme objects requires continuous all-sky coverage, while detailed study demands an improvement in sensitivity over previous technologies by at least an order of magnitude. The DUAL payload is composed of an All-Sky Compton Imager (ASCI), and two optical modules, the Laue-Lens Optic (LLO) and the Coded-Mask Optic (CMO). The ASCI serves dual roles simultaneously, both as an optimal focal-plane sensor for deep observations with the optical modules and as a sensitive true all-sky telescope in its own right for all-sky surveys and monitoring. While the optical modules are located on the main satellite, the All-Sky Compton Imager is situated on a deployable structure at a distance of 30 m from the satellite. This configuration not only permits to maintain the less massive payload at the focal distance, it also greatly reduces the spacecraft-induced detector background, and, above all it provides ASCI with a continuous all-sky exposure.

Keywords Nuclear astrophysics · Gamma-ray optics: Compton telescope · Laue lens · Coded aperture imaging · Second cosmic vision call of ESA

The full author list and affiliations are given at the end of the paper.

The DUAL Consortium
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1 Introduction

Most of the radiation that we observe from the Universe arises from thermal emission processes that occur during relatively quiet phases of cosmic evolution, providing us with snapshots of processes that last millions to billions of years. Some of this radiation, however, originates in explosive events or non-thermal processes, which are capable of accelerating particles to the most extreme energies, and which provide the conditions to synthesize the elements we are made of.

Gamma-ray observations play a unique role in the study of these explosions and relativistic particle accelerators. Electrons accelerated to relativistic energies radiate γ-ray photons through electromagnetic interactions with nuclei, photons, or intense magnetic fields. Accelerated protons generate secondary particles through nuclear interactions, which decay by emission of high-energy γ-ray photons. At γ-ray energies, de-excitations in the atomic nucleus lead to characteristic line features, analogous to features at longer wavelengths that are caused by electronic transistions. Two of the most important processes that produce γ-rays are the radioactive decay of freshly-produced isotopes, allowing the direct study of nucleosynthesis processes that occur in the deep interiors of stars and supernovae, and the annihilation of electrons and positrons, which results in a unique signature at 511 keV that allows the study of antimatter in the Universe.

The sites of γ-ray emission in the Universe are very diverse, reaching from our Sun out to the γ-ray bursts (GRBs) at redshifts $z > 8$ and to the cosmic γ-ray background radiation of the early Universe. Cosmic acceleration manifests itself prominently in cosmic rays, which are best studied remotely in γ-rays, and takes place locally in solar flares, within our Galaxy in compact binary systems, pulsars and pulsar wind nebulae, supernova remnants, and in extremely distant objects such as active galactic nuclei and GRBs. Cosmic explosions are a site of prominent γ-ray emission, allowing examination of a wealth of radioactive isotope production, sources of antimatter, and accelerated particles at relativistic energies. Novae, supernovae and hypernovae are thus prime targets of γ-ray astronomy.

A key feature of γ-rays is that they are highly penetrating, allowing the study of otherwise obscured regions. Examples are regions of the galactic disk hidden by dense interstellar clouds, or the deeper, inner, zones of accretion-, nuclear-, or gravity-powered sources. Indeed, in these cases, γ-ray emission is the most fundamental emission process at work. New classes of sources appear in the γ-ray domain, which are invisible otherwise.

In summary, γ-ray astronomy provides a unique and novel view of our Universe. It unveils details of emission processes, a large diversity of emission sites, and probes deeply into otherwise obscured high-energy engines. The γ-ray Universe is the that of particle acceleration and nuclear physics, of cosmic explosions and non-thermal phenomena. Exploring the γ-ray sky means exploring a unique face of our world, the face of the evolving violent Universe.

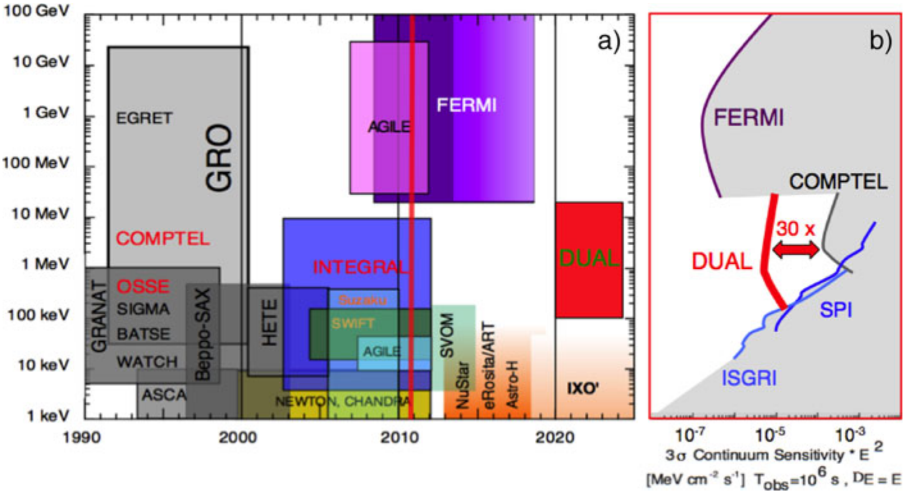


Fig. 1 A bridge across the MeV-Gap. The roadmap of high energy astronomy shows a white spot on the future track of nuclear astrophysics—i.e. in the energy range of 100 keV–100 MeV (**a**). The missing link not only is a concern for the future, there already exists a deep sensitivity gap (**b**) with on one side focusing X-ray instruments, and on the other side, imaging tracking detectors in the GeV and TeV range with extremely low background. With a sensitivity leap by a factor of 30, DUAL will bridge this gap, addressing a wide range of fundamental astrophysical questions such as the life cycles of matter and the behaviour of matter under extreme conditions by providing sensitive γ-ray spectroscopy, and for the first time, true γ-ray polarimetry

Following more than eight years of successful operations, INTEGRAL has significantly changed our vision of the Universe through its observations of the γ-ray sky. The instruments aboard the satellite have revealed hundreds of sources of different types, new classes of objects, the fingerprints of recent nucleosynthesis and extraordinary and puzzling views of antimatter annihilation in our Galaxy. The IBIS and SPI telescopes have provided medium-sensitivity surveys of the hard X-ray and soft γ-ray sky, with a census of the source populations and first-ever all sky maps in this so far unexplored energy range.

The exploration of the soft γ-ray band is complementary to the progress that is presently being made in neighbouring energy bands. On the X-ray and hard X-ray side, at the limit of the onset of non-thermal astrophysics, a large number of missions are underway (NuStar, Astro-H, eROSITA...) or under study (the IXO assessment study lead by ESA, to mention only one mission concept amongst many). Across the MeV-Gap (Fig. 1), Fermi is presently revolutionizing the landscape in the high-energy γ-ray sky at GeV energies, and very high-energy γ-rays detected by ground based Cherenkov telescopes (such as HESS, MAGIC or VERITAS) have conquered this part of the spectrum for astronomy, with sources mainly belonging to the classes of pulsar wind nebulae, supernova remnants, blazars and micro-quasars.

A majority of the most energetic compact objects in our universe, AGN, have their peak emission in the MeV range. Thus, only through observations in this range will we finally be able to fully test emission models for these sources. Understanding high-energy emission processes relies heavily on a broad spectral coverage, and combining DUAL observations with those achieved up to tens of keV on the one side, and the progress at GeV and TeV energies on the other side, will provide unique constraints on the underlying physics.

However, DUAL not only provides a vital bridge between X-ray and high-energy γ-ray astronomy, it will actually *fill* the sensitivity gap that has opened over the last decades in the nuclear range. Since the first generation of γ-ray telescopes in the early 1980's, three generations of space instruments (HEAO, Compton GRO, INTEGRAL) have consecutively observed the nuclear band, improving the sensitivities by a factor of roughly 7 (e.g., in the crucial ^{56}Co line at 847 keV). DUAL will provide the long awaited leap of a factor of 30, both for the ^{56}Co and ^{56}Ni (812 keV) lines of SN Ia, during focused pointings (10^6 s) of its Laue lens, and for the long-lived radioactivity, e^+e^- annihilation radiation, nuclear excitation lines, etc. during its all-sky survey, through a very deep exposure ($\sim10^{10}$ cm^2 s) of every source in the entire sky.

2 Scientific objectives

2.1 The evolving violent Universe seen in γ rays

The observation of γ rays allows the exploration of the most violent places in the Universe. Gamma-ray observations unveil the most extreme conditions known, where the densest objects heat matter to temperatures of billions of degrees, where the strongest magnetic fields accelerate particles to the most extreme energies, and where the most energetic radiation fields create matter from pure light. These extreme conditions occur generally at the endpoints of stellar lives, when the relatively calm thermal evolution gives way to a more violent non-thermal evolution. Stellar explosions of all kinds and particle acceleration processes play a key role in this evolution, providing the conditions to synthesize new elements and providing kinetic energy to the interstellar and intergalactic media that are the seeds for new generations of stars and galaxies.

The cosmic variety of elements, which forms also the foundations of biological life, has largely been generated inside supernova explosions. The injection of kinetic energy by these explosions into the interstellar medium drives the mixing processes of interstellar gas, which finally leads to the formation of next generations of stars. Supernovae shocks are thought to be the sites of particle acceleration up to cosmic-ray energies. Supernovae are among the brightest sources of light in the Universe, observable out to large redshifts. GRBs have been recognized to constitute one variety of massive-star supernovae, the collapsars, at least for the long-duration GRBs. Consequently, supernovae and GRBs are prominent tools to probe the early Universe.

Cosmic explosions At the endpoint of stellar evolution, gravity ultimately dominates over energy released through nuclear fusion, in the case of a massive star leading to a violent explosion. Observing γ-ray line signatures from radioactive trace isotopes synthesized during such explosions is a powerful means to probe the physical conditions and mechanisms that drive these events. While the evolution of less massive stars into white dwarf remnants is not accompanied by explosion, the remnant's strong gravitational field still has the potential for catastrophic events. Mass accretion onto white dwarfs in a close binary system can lead to thermonuclear explosions at the star's surface, and γ-ray observations of radioactive trace isotopes synthesized during these explosions tell us about the mixing and convection processes that regulate these events. Eventually, the white dwarf may also be disrupted catastrophically by a central thermonuclear explosion, leading to a bright Type Ia supernova (SN1a) event that can be observed to considerable distances across the Universe. Again, γ-ray observations of radioactive species that are synthesized in these events will allow us to better understand how these explosions work.

Cosmic accelerators The remnants of stellar explosions are powerful sites of particle acceleration. Rapidly rotating magnetized neutron stars left over by the core collapse of massive stars manifest themselves as pulsars that directly accelerate particles by their huge magnetic fields. Where and how this acceleration process operates is still unclear and will be more clearly revealed by γ-ray observations. In particular, γ-ray timing and polarization measurements provide unique tools to assess the geometry and location of the particle acceleration site. Shock waves generated by the expanding supernova remnants accelerate particles in a slow but continuous process to extreme energies, and are thought to produce the bulk of cosmic radiation contained in the Galaxy. Soft γ-ray observations of supernova remnants probe the low-energy part of the acceleration process, and are able to unveil the injection mechanism of particles into the shock front. Compact stellar remnants in binary systems, such as neutron stars or black holes, are another important acceleration site, where a fraction of the matter that is accreted by the strong gravitational field is accelerated into collimated relativistic jets. Active galactic nuclei, with their super massive black holes, are scaled-up versions of the same naturestellar mass variety. γ-rays probe the innermost regions of the accreting systems that are not accessible in other wavebands, providing the closest view to the acceleration engine. Time variability and polarization studies provide important insights into the physical processes and the geometry that govern the acceleration site. The observation of characteristic nuclear and/or annihilation line features may help to settle the question about the nature of the accelerated plasma.

Positron production potentially occurs in a variety of cosmic explosion, accretion, and acceleration sites, and the observation of the characteristic 511 keV annihilation line signature and the accompanying three-photon continuum provides a powerful tool to probe plasma composition, temperature, density and ionization. The positron annihilation signature is readily observed from the galactic bulge region yet the origin of the positrons there remains mysterious. By searching for such signatures in a variety of objects, DUAL not only will constrain their physical conditions, but may also provide the key to the understanding of the galactic positron origin.

Last but not least, annihilation of light dark matter has been proposed as possible origin of the galactic positrons. Although highly speculative, the importance of identifying the nature of dark matter justifies the search for observational signatures in all wavelength domains. The γ-ray domain is here unique, in the sense that it allows the observation of the annihilation of the lightest charged leptons that should be at the endpoint of any annihilation process. By the observation of nearby dwarf galaxies that are rich in dark matter, DUAL can provide important constraints on the viability of the light dark matter scenario.

2.2 Science drivers

2.2.1 Understanding the physics of supernova explosions

Thermonuclear supernovae yield profound results for modern precision cosmology—the accelerating Universe, yet we do not understand their progenitor systems, the initiation or propagation of nuclear burning, the origin of the observed variation in peak luminosities, or its metallicity dependence. Measurements of ^{56}Ni masses and distributions in a sample of nearby events will help clarify the physics of SN Ia.

- What are SN Ia progenitor systems?
- What produces the variation in ^{56}Ni mass and peak brightness?
- How does the nuclear flame proceed through the white dwarf?

A direct view of ^{56}Ni–^{56}Co in Type Ia supernova explosions is required to answer these questions, understand their explosion mechanism and solidify their use as standard candles for Cosmology. A conservative estimation from the Sternberg catalogue indicates that with a sensitivity of $\sim 2 \times 10^{-6}$ ph/cm^2/s, the Laue lens of DUAL will determine from the ^{56}Co 847 keV line the amount of ^{56}Ni synthesized during the explosion, for a sample of at least $\sim$30 supernovae of all subtypes during a period of 4 years. Also the ASCI can measure the complete evolution of the spectrum of any SN Ia that fortuitously occurs at distances smaller than 6 Mpc.

2.2.2 Gamma-ray burst spectroscopy and polarization

Broadband spectroscopy combined with measurement of the polarization of the γ-ray radiation emitted during the prompt Gamma-Ray Burst emission is crucial diagnostics for solving the prompt emission mechanism issue. By considering the $\sim$full-sky FOV of the DUAL/ASCI and its L2 orbit, and scaling rates from previous GRB missions to the DUAL energy range, about

600 GRBs/yr should be detected. DUAL will be sensitive to a polarisation level of 50% for ~60 GRBs per year, and to a level of 10% for about 20 GRBs per year. A level of 10% is very constraining for models and is the level of optical polarisation which has been observed in a very few early afterglows.

DUAL will derive an unprecedented global picture of spectral characteristics for this sample over the mission lifetime which will inform and constrain future theoretical work in GRB acceleration and radiation mechanismsthe existing models—e.g. diffusive shock acceleration, proton acceleration v.s. magnetic field reconnections in highly relativistic outflows, and quasi-thermal Comptonisation; the mission will launch new theoretical studies in GRB acceleration and radiation mechanisms.

2.2.3 Antimatter in the Galaxy—positron astrophysics

The recent INTEGRAL/SPI all-sky map of the galactic positron annihilation radiation shows emission strongly concentrated in the Galactic Bulge but with evidence of a significant disk asymmetry [16]. This bright, diffuse emission exhibits an angular distribution that defies a simple explanation.

- What is the source of the Galactic positrons?
- What is the morphology of the diffuse emission?
- What is the role played by dark matter annihilation?

Over a 3-year mission, DUAL will map the 0.511-MeV line and its associated positronium continuum (integrated line flux $\sim 10^{-3}$ γ cm^{-2} s^{-1}) with a S/N ratio $>100\sigma$ DUAL will provide high resolution spectroscopy over the entire sky with an angular resolution of about 3°, and in the Galactic Bulge with a resolution better than a degree (i.e. 12′ to 54′). With the combined maps and spectral information, DUAL will investigate the contributing sources and annihilation sites in unprecedented detail. Revealing the distribution and ultimately the origin of galactic positrons is a primary science goal of DUAL.

2.2.4 Radioactivities in the Galaxy

DUAL will provide a deep all-sky exposure of ^{26}**Al,** ^{60}**Fe and** ^{44}**Ti**, over its 3-year survey, with a 30× improvement in narrow-line sensitivity compared to COMPTEL and high spectral resolution, helping to answer these questions:

- What are the roles of various star formation pathways in creating elements?
- How variable is production of radioactivity in individual massive stars and SN?
- What is the recent history of core collapse supernovae?

Classical novae DUAL's continuous full sky coverage is crucial for the detection transient annihilation γ-ray emission which happens before a nova is discovered optically. DUAL will detect the annihilation emission in at least

1–2 novae per year. DUAL will also enable the detection of long duration ^{22}Na γ-ray lines. Around 2–3 novae per year are expected at ∼3–4 kpc distances and 1/4–1/3 of them should be ONe; thus, novae could be detectable with DUAL at a rate of ∼1 per year.

2.2.5 Low-energy cosmic rays: nuclear de-excitation lines

Collision of cosmic rays with interstellar matter is expected to produce a wealth of γ-ray lines of energies between 0.1 and 10 MeV. Spectroscopic observations of this γ-ray emission with DUAL will address some of the most fundamental questions concerning the physics of the Milky Way:

- What is the origin of Galactic cosmic rays?
- What is the exact role of low-energy cosmic rays in the self-regulation of the Galactic ecosystem?
- What is the production rate of the light elements Li, Be and B synthesized by inelastic collisions between cosmic rays and interstellar nuclei?

Since the solar modulation effect makes direct detection of sub-GeV cosmic rays near Earth impossible, the nuclear γ-ray line emission produced by interaction of low-energy cosmic rays with interstellar nuclei represents the best chance to get information about the flux, spatial distribution and composition of the accelerated particles.

2.2.6 Matter under extreme conditions: compact objects

Isolated neutron stars The youngest **pulsars** tend to be at their brightest in the MeV range. Observations in the soft γ-ray domain by DUAL will therefore play a decisive role in discriminating between the model classes and in probing particle acceleration in such extreme environments.

- What is the particle acceleration mechanism in young pulsars?

DUAL observations of **magnetars** will yield the first precise location and shape of the spectral break, thereby significantly constraining the theoretical models, mostly based on acceleration of particles in twisted magnetic loop configurations. Also, polarization measurements enabled for the first time by DUAL, will provide an independent and unique tool to nail down the emitting processes in these intriguing objects.

- What is the location and shape of the spectral break in magnetars?

DUAL will also substantially increase the sample of persistent **pulsar wind nebulae** detections at soft γ-rays, thus enabling the first population studies.

Accreting Galactic Compact Objects Physical processes in systems with accreting black holes operate to produce non-thermal components that extend to >MeV energies. However, these components have not been well characterized due to lack of sensitivity by previous 1–10 MeV missions, and their origin is not well understood. The unprecedented DUAL sensitivity will allow for the first measurements of the non-thermal components from dozens of black hole binaries.

- How high in energy does the non-thermal component from accreting BHs extend, and what are the detailed requirements for the process of accelerating electrons?
- What is the rate of positron production from accreting BHs with jets, and what fraction of the Galactic bulge 511 keV emission can be attributed to X-ray binaries?
- Does the polarization of γ-rays from accreting compact objects indicate an origin for this emission in the disk or in the jet?
- Using the nuclear 2.2 MeV line, what is the gravitational redshift at the surface of the neutron star, and what is the neutron star equation of state?

A foremost motivation for DUAL observations of X-ray binaries is the measurement of the **γ-ray polarization**, which is highly discriminating between emission mechanisms and source geometries but which has not been previously available at X-ray or γ-ray energies.

Active galactic nuclei The MeV energy range is crucial for our understanding of the processes driving active galactic nuclei. Flat spectrum radio quasars, the most energetic compact objects in our universe, have their peak emission in the MeV range. Thus, only through observations in this range will we finally be able to verify emission models for this type of object.

It will be possible for the first time to determine to the total energy output of beamed sources in the Universe. This will answer questions like:

- How much energy is injected into the interstellar and intergalactic medium by blazars?
- How important is particle injection for the star burst evolution in the host galaxies?
- How do AGN contribute to the life cycle of matter?
- What sources dominate the so far unresolved γ-ray background?

After a three year DUAL mission on the order of 1000 AGN will be detected, out of which about 10% will be BL Lac objects.

2.2.7 Solar physics

The tremendous explosions occurring from time to time on the surface of our Sun are sources of major disturbances in the nearby interplanetary space. Gamma-ray astronomy is one of the best tools for studying the active Sun. Gamma-ray lines are emitted in large solar flares from positron annihilation, secondary neutron capture and de-excitation of nuclei excited by interactions of flare-accelerated ions with the solar atmosphere. Hard X-ray continuum emission is also produced from bremsstrahlung of accelerated electrons. Fundamental questions concerning this energy release and the associated particle acceleration include the following:

- What triggers these solar energetic events? Is it possible to predict them with accuracy?
- What mechanisms accelerate so rapidly and efficiently electrons and ions to GeV energies?
- How do the energetic particles propagate from their acceleration site in solar flare magnetic loops to their interaction regions deeper in the solar atmosphere?
- What is the exact relationship of solar flare accelerated particles to solar energetic particles observed in the interplanetary medium

For DUAL to be able to perform detailed observations of prompt solar flare emissions, such a flaring active region will have to be rapidly declared a Target of Opportunity for the instrument. Three important γ-ray line features are emitted in the DUAL energy range: the "$\alpha - \alpha$ line complex" at ~450 keV produced by interactions of accelerated α-particles with ambient ^{4}He, the e^+–e^- annihilation line at 511 keV, and the 847 keV line from ambient ^{56}Fe excited by collisions with energetic protons and α-particles. Thanks to the unprecedented sensitivity obtained with the Laue crystal lens, DUAL will be able to carry out for the first time detailed imaging spectroscopy of these three γ-ray lines, specially of the 847 keV line.

DUAL has the potential to observe for the first time this solar radioactivity. Such detection will provide a new insight into the acceleration of heavy ions in solar flares, because the radioisotopes are expected to be predominantly produced by interactions of fast heavy ions with ambient hydrogen and helium. Perhaps more importantly, the radioisotopes synthesized in flares can serve as tracers to study mixing processes in the solar atmosphere. The delayed lines should be strongly attenuated when the radioactive nuclei plunge deep in the solar convection zone. The spectro-imaging capabilities of DUAL will allow measurements of the size and development of the radioactive patch on the solar surface.

2.3 DUAL mission requirements

The bottom line we deduce for a next generation γ-ray mission is the requirement for an improvement in sensitivity by a factor of 30 for the key science drivers. Whereas the demand for such sensitivity comes from a majority of science drivers, the various scientific objectives feature emission with a wide range of angular and spectral extent, varying in intensity by several orders of magnitude. Many interesting scientific questions are in a domain where photons are rare, and therefore *large collection areas or very long observations* are needed. The scientific objectives for γ-ray spectroscopy span the range from compact sources such as local supernovae, galactic and extragalactic compact objects, long-lived galactic radioisotopes with hotspots possibly in the degree-range, to the extremely extended galactic disk and bulge emission of the narrow e^+e^- line, to the isotropic γ-ray background.

Candidate sources of high intensity are mostly galactic and include the sites of recent nucleosynthesis, regions of e^+e^- annihilation and clouds where nuclear de-excitation by energetic particles takes place. Some of them might appear as extended structures: either because of their apparently diffuse origin—as in the case of narrow 511 keV line—or because they are relatively close as the nucleosynthesis sites in the local spiral arm (^{26}Al in the Vela, Cygnus or Sco-Cen region). An instrument that is adequate for this kind of objective should provide a narrow line sensitivity of a few 10^{-6} ph$\cdot$ cm$^{-2}\cdot$ s^{-1}, a wide field of view and an angular resolution in the degree range. Since these types of emission do not vary over time, long exposures may be employed. The constraints above are in contrast to the requirements for the observation of radioactive ^{56}Co from Type Ia supernovae—certainly one the most pressing astrophysical questions of our age. Here we face rapidly decaying broad line emission from a point source. In order to cover these objectives (lower left of Fig. 2), deep observations of selected narrow-field targets have to be performed in a limited time—necessitating a telescope of unprecedented sensitivity.

Last but not least, γ-ray emission may be substantially polarized due to the non-thermal nature of the underlying emission processes such as pulsars, accreting black holes etc. Studying not only the intensity and the spectrum but also the polarization of the emission adds a new powerful scientific dimension, discriminating between the different plausible emission processes at work and constraining the geometry of the emission sites. A sensitive measurement of

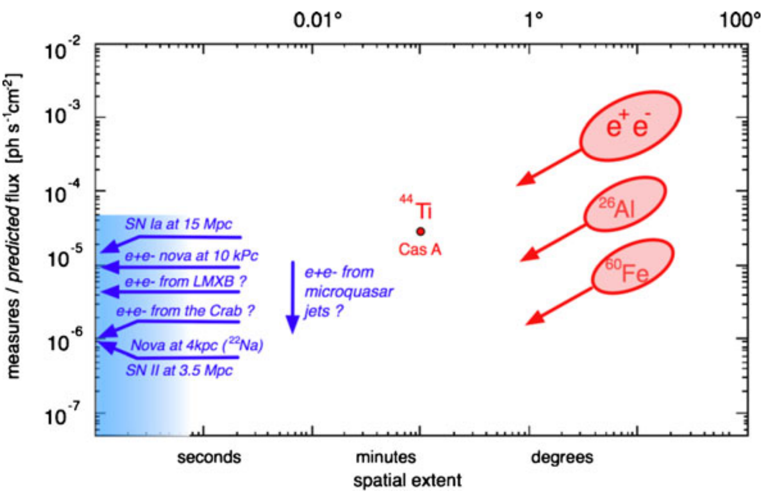


Fig. 2 A future γ-ray mission has to face emissions with a wide range in angular extent and with intensities differing by several orders of magnitude: The requirements can naturally be divided into two subsets: a requirement for medium-sensitivity large-scale exposures and very deep pointed observations

the polarization is not only required for the above mentioned populations of compact sources, but will be of capital interest for the study of the prompt emission of γ-ray bursts.

The above requirements naturally can be divided into two subsets: a requirement for medium-sensitivity large-scale exposures, and very deep pointed observations. This duality is naturally addressed by the DUAL mission concept, which employs an All-Sky Compton Imager (ASCI) performing true all-sky surveys in combination with two optics modules; both Optics modules utilize the ASCI as their focal plane. The Laue-lens (LLO) enables simultaneously very deep observations of selected SN Ia. Compton Telescopes are very good wide field cameras but have an intrinsic problem with a relatively modest angular resolution.

Through the Coded Mask Optic (CO), which enhances the angular resolution dramatically (10′–40′), this problem is overcome in the Galactic Bulge region—one of the densest and most enigmatic regions of the sky. Based on the scientific goals presented above, the DUAL mission requirements are summarized in Table 1. The major requirement for the next generation γ-ray mission is a significant improvement in sensitivity, by at least an order of magnitude with respect to existing and previous instrumentation.

Mission profile The DUAL mission profile and system architecture has been studied in a dedicated industry study by Thales Alenia Space (TAS). We present here the results of this study as baseline for the DUAL mission profile.

The DUAL mission is composed of one spacecraft that will be launched from Kourou by a Soyuz Fregate-2B launcher. The mass and layout of the satellite associated with Soyouz performances open the possibility to consider a dual launch with another L2 mission. The spacecraft carries two optics modules, the Laue Lens Optic (LLO) and a Coded Mask Optic (CMO) that both focus incoming γ-rays onto a focal plane detector (ASCI) located at the end of a 30 meters-long mast. Besides of serving as focal plane detector, the ASCI (All-Sky Compton Imager) is a ground-breaking new instrument concept by itself: ASCI continuously observes every single γ-ray source in the sky during 3+ years—i.e. the entire mission lifetime. Figure 3 illustrates the DUAL mission profile. The satellite is launched in a direct transfer trajectory towards the L2 point. During the cruise, the satellite will be checked through

Table 1 DUAL mission requirements

Parameter/Objective	GC positrons	SN Ia	GRB
Energy coverage	0.2–0.6 MeV	800–900 keV	20 keV–10 MeV
Line sensitivity ($\Delta E/E = 3\%$)	3.10^{-6} γ cm^{-2} in 3 y	10^{-6} γ cm^{-2} s^{-1} in 10^6 s	–
Energy resolution (FWHM)	0.5%	1%	0.5%
FoV	4 π steradian	10 arcmin	4 π steradian
Angular resolution	1°	–	1°
Timing	–	–	100 μs
Polarimetry (MDP, 3 σ)	–	–	5% for 100 mCrab

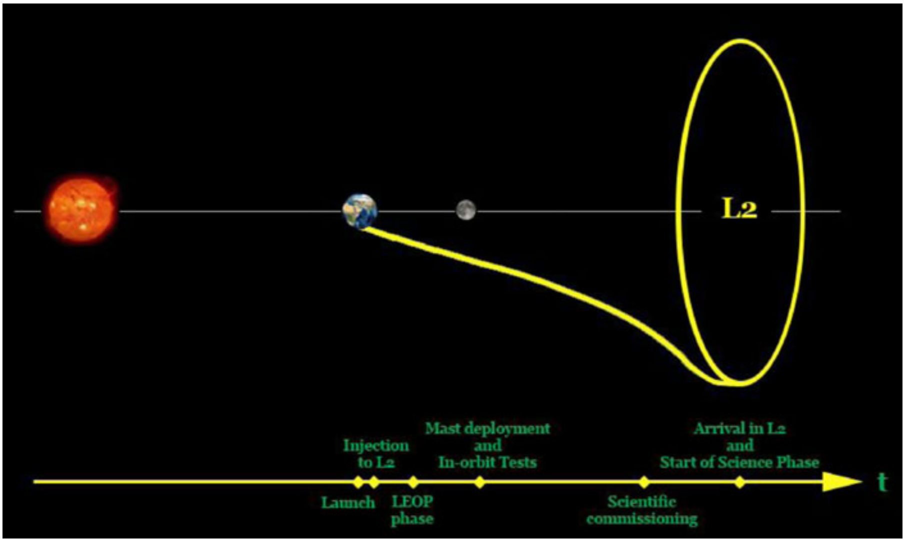


Fig. 3 Overview of the Mission overview—DUAL mission.is launched in a direct transfer trajectory towards the Sun–Earth L2 point

In-Orbit Tests (IOT) and configured with the mast deployment to its nominal length and Sun acquisition by the Solar Arrays. Once arrived in its final orbit, after a scientific commissioning phase, a science phase of 3 + 1 years will follow.

Launcher and orbit requirements The L2 position selection associated with the DUAL satellite mass and dimensions imply the use of a Soyuz Fregate-2B launch. However, the launcher performances open the possibility to perform a dual launch with a co-passenger that requires a L2 position as well. To accommodate for the dimensions of both spacecrafts, the ST fairing will be employed (see Fig. 4). The two satellites accommodation under the fairing will have to be studied, with the possible use of the SYLDSO adapter. The heaviest satellite will be placed at the bottom, and will be supported by the Soyuz-Fregate standard adapter (1194-SF). The lighter satellite will be placed on top of the SYLDSO interface (TBC). Including the necessary S/C adapter, the DUAL total launch mass (including all sub-system margins as well as a 20% system margin) amounts to 1154 kg, leaving 946 kg to the co-passenger and its adapter with respect to the launcher performances (see Table 2). The drivers for an L2 orbit are both scientific and technological. The extraordinary performance of DUAL's All-Sky Compton Imager (ASCI) is only made possible by its distance to large masses (earth, spacecraft): in L2, Albedo background radiation from the earth can be avoided, moreover, the entire (4π!) sky is available for simultaneous observation, resulting in a more than four times enhanced exposure for every source in the sky (w/r the a LEO). Also, a high orbit is reducing the gravity gradient, facilitating maneuvers and

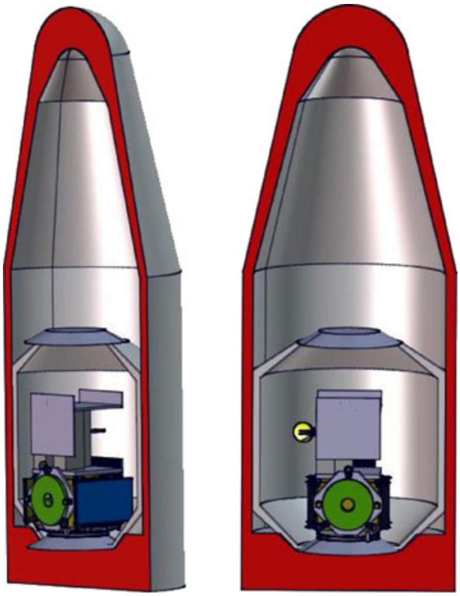


Fig. 4 Accommodation of the DUAL satellite in stacked configuration in the Soyuz Fregate-2B ST

pointing demands of DUAL's 30 m long configuration and permits simple passive cooling of the detector to 80–100 K. Last but not least, with the Earth, the Sun and the Moon being always in roughly the same direction, scientific requests for ToO pointings (SN1a) are easier to comply with, since conflicts of S/C orientation are relaxed (scientific pointing requests, vs. solar arrays-, radiator-, antenna-orientation).

Ground segment All communications to the satellite will be performed using a single ESOC 15 m antenna using the X-band. In order to reduce operational costs, a limited number of specific telemetry sessions will be defined that allow commanding and downlink of science and housekeeping data. With such a ground antenna, the data downlink will be performed at an estimated data rate of 1.6 Mbps. With a 8 h visibility duration, this data downlink profile

Table 2 The DUAL global mass budget

Item	Mass [kg]
Service Module mass	441
Payload Module mass (mature) ASIC (112), LLO (80), CMO (113) Mast (73)	378
Satellite dry mass	819
20% system margin	164
Hydrazine	50
Satellite total mass (with contingency)	1033
Adapter mass	121
DUAL mass at launch	1154
Soyuz-Fregate capability	2100
Mass reserve (available for Co-passenger)	946

allows up to 45 Gbits of data acquisition per day which is compliant with global DUAL mission requirements. This data-rate will require no on-board data compression nor data downlink optimisation.

3 Payload

3.1 Overview

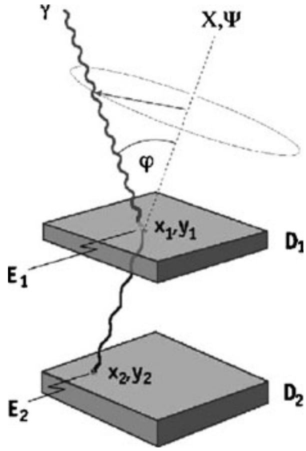
The DUAL payload is composed of an *All-Sky Compton Imager (ASCI)*, and two optical modules, the *Laue-Lens Optic (LLO)* and the *Coded-Mask Optic (CMO)*. The *ASCI* serves dual roles simultaneously, both as an optimal focal-plane sensor for deep observations with the optical modules and as a sensitive true all-sky telescope in its own right for all-sky surveys and monitoring. It is situated on a deployable structure at a distance of 30 m from the satellite. The mass of the three payloads including the Collapsible Tube Mast (CTM) totals under 400 kg. The DUAL payloads have been studied by dedicated industry studies by TAS (lens, payload) and Canberra (detector). The following sections describe the results of these studies.

Combining a Compton telescope with a Laue lens and a coded mask will permit to meet the apparently irreconcilable requirements for a future γ-ray mission (see Fig. 2). While the ASCI performs its "all-sky science"—i.e. map out large-scale distributions (e+e- annihilation radiation, long-lived radioactivities, excitation lines), detect GRB's on the entire sky and measure their polarization, monitor a large number of extragalactic and galactic compact sources—the optics modules simultaneously focus on specific key targets. The LLO concentrates on freshly produced radioactivity as a key to understanding SN1a (LLO), and the CMO will disentangle the emission of compact objects in the Galactic Center, and map out the as yet unresolved bulge of e^+–e^- annihilation.

The principle of Compton imaging of γ-ray photons is illustrated in Fig. 5. An incoming photon of energy E_g undergoes a Compton scatter at a polar angle θ with respect to its initial direction at the position r_1, creating a recoil electron of energy E_1 that induces the signal measured in the detector. The scattered photon then undergoes a series of one or more interactions (E_i, r_i), which are also measured. The Compton formula (below) relates the initial photon direction to the scatter direction (measured direction from r_1 to r_2) and the energies of the incident and scattered γ-rays.

But how can such small instruments (each one with $m \leq 100$ kg) achieve science goals that require a factor of 30 improved sensitivity compared to previous telescopes—some of them being an order of magnitude larger, i.e. more massive? Traditionally, realizing more sensitive γ-ray instruments is first of all associated with enhancing the source exposure (E), which then usually was translated with enhancing the instrument area (A_{eff}). However, larger photon detectors are not only more massive, they also have higher volumes and

Fig. 5 Principle of a Compton Telescope



hence go along with higher instrumental background, so sensitivity improves at best with the square root of the size of the instrument. Two ground-breaking first-time ever concepts permit DUAL to overcome this impasse, resulting in performances that are worthy of much larger instruments:

ASCI—"time has no mass": as a true "whole sky telescope", ASCI will observe every single source in the sky during its *entire mission lifetime* (T_{life}) yielding extraordinary exposures for all those sources, even with the modest mean effective area ($\hat{A}_{eff}$) of a small instrument. Here a large exposure is produced by the *very long* observation time ($E = A_{eff}\ T_{life}$); and while the Compton condition keeps a background low, the sensitivity dramatically increases. In comparison with a 0.1 ster FoV instrument observing a source during 10^6 s (like SPI), ASCI (FOV: 12 ster = > $T_{life} = 10^8$ s) has an exposure (multiplex) advantage of 100, resulting in a sensitivity improvement of one order of magnitude.[1]

LLO—large area but low background focusing source photons from the *large collecting area* (A_{lens}) of the LLO onto a small detector volume of the ASCI yields extraordinary exposures for the sources pointed, even for relatively short exposure times. Since the volume producing background noise is very small, Signal-to noise ratio (SNR) are extremely high and unprecedented sensitivities are achieved.

Remarkably, both concepts, the whole-sky telescope (ASCI) and the γ-ray lens (LLO), are best realized by using a mast. A detector on the tip of a mast not only allows DUAL to maintain the less massive payload at the focal distance of a γ-ray lens, it also grants an unobstructed all-sky view to a true 4π -steradian imager. Here, the entire sky becomes available for simultaneous

[1] See Appendix.

observation, resulting in a more than four times enhanced exposure for every source in the sky with respect to an equivalent instrument in LEO.

Background considerations Besides of the all-sky multiplexing advantage, keeping the detector away from the platform cuts down background induced by cosmic-ray interaction in the spacecraft. This effect has been observed for the first time with a small γ-ray detector deployed on a 7.6 m boom from the Apollo 15 service module, resulting in background reduction of an order of magnitude due to the reduced solid angle subtended by the spacecraft [14]. However, this solid angle effect can only be beneficial if albedo background radiation from the earth's atmosphere is avoided. Far from the atmosphere, and without a spacecraft stuck underneath the detector, there is no need for a shield or a time-of-flight electronics to suppress events coming "up" through the detector: in such a configuration, the events from coming from above and the ones coming from below have equal probabilities to be signal (see Fig. 6 for the effect of upwards moving events in CGRO-COMPTEL and Fig. 7, the various options for reducing this important background component). The photon energy, direction and polarization are reconstructed from the measured quantities (interaction positions and energies) for the various possible event sequences. The most probable direction of motion is then calculated using Bayesian statistics: a quality factor is assigned to each event describing the probability that the given event sequence is correct and originated from a completely absorbed photon.

As shown in Section 2.3, sensitivity *is* the foremost demand for a future γ-ray mission; the combination of an All-Sky Compton Imager with a Laue Lens is filling the stringent requirements. However, Compton telescopes have

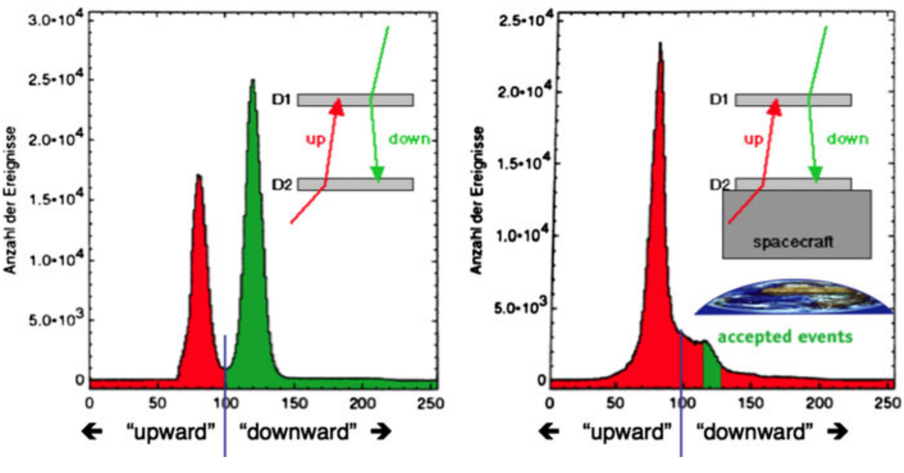


Fig. 6 The time of flight spectra of CGRO-COMPTEL: *left*) time of flight for downward and upward moving photons during ground calibrations at Neuherberg. Discrimination seems evident. *Right*) time of flight spectrum in low earth orbit: upward-moving photons from earth and spacecraft albedo are dominating the background

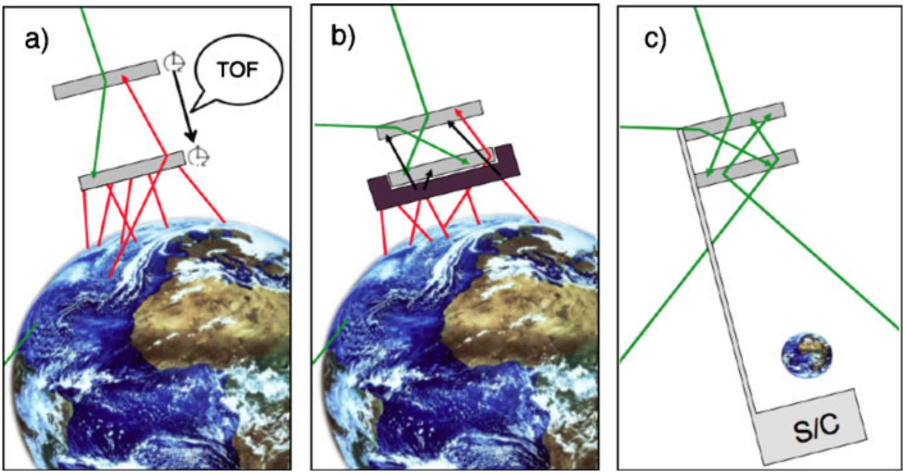


Fig. 7 Options for suppressing earth and spacecraft albedo background: **a** Time of flight measurement: requires wide detector spacing resulting in low detection efficiency, leading to high instrument masses. **b** Anticoincidence shield: their mass is usually superior to the detector's, leading to very massive instruments. **c** High orbit, on a mast: avoid earth and s/c background and benefit of a 4 times larger FOV, synonymous with 4 times more signal—this is **the DUAL choice**!

inherent limitations in angular resolution, fundamentally limited below a few hundred keV by the fact that the target electrons have an indeterminable momentum inside their atoms which introduces an uncertainty in the recoil energy of the Compton electron and the scattered photon [17]. For ASCI, this means that, e.g., the maps of GC annihilation radiation are limited to resolutions of 2.5° at best (strong source). This is the same order of what is presently achieved by SPI, even though ASCI will provide a sensitivity improved by more than an order of magnitude. We therefore propose to improve considerably the imaging capabilities of DUAL by a coded mask optic that will be situated on the spacecraft. The important distance between S/C and ASCI will result in spectacular angular resolutions (10–50 arcmin) that will be most valuable in the Galactic Center region. The performance of the three DUAL payloads is summarized in Table 3.

3.2 All-Sky Compton Imager (ASCI)

Situated on a deployable structure at a distance of 30 m from the satellite, the ASCI is a compact array of cross-strip germanium detectors, with high spectral and 3-D spatial resolution to track γ-ray Compton-scatter interactions. The ASCI serves dual roles simultaneously, both as an optimal focal-plane sensor for deep observations with the optical modules and as a sensitive true all-sky telescope in its own right for all-sky surveys and monitoring. It will perform sensitive γ-ray spectroscopy and polarimetry in the energy band 100 keV–10 MeV Although weighting under 100 kg, ASCI's γ-ray line sensitivity after

Table 3 DUAL payload characteristics and performance

ASCI: All-Sky Compton telescope		
Energy range		0.1–10 MeV
Spectral resolution (10 MeV–0.1 MeV)		0.2–1% FWHM
Field of view		$4\,\pi$ at all times
Angular resolution	511 keV	2.7° (4.5° at sensitivity limit)
	847 keV	2.1° (3.5° at sensitivity limit)
	1809 keV	1.6° (2.7° at sensitivity limit)
Narrow line sensitivity		
(any DC source after $T_{obs} = 3$ year)	511 keV	$2.6{\cdot}10^{-6}$ ph·cm^{-2}·s^{-1}
	847 keV	$1.1{\cdot}10^{-6}$ ph·cm^{-2}·s^{-1}
	1809 keV	$7.2{\cdot}10^{-7}$ ph·cm^{-2}·s^{-1}
Continuum sensitivity	500 keV	$4.2{\cdot}10^{-5}$ ph·cm^{-2}·s^{-1} MeV^{-1}
(any DC source, $T_{obs} = 3$ year)	5 MeV	$1.5{\cdot}10^{-6}$ ph·cm^{-2}· s^{-1} MeV^{-1}
Polarization sensitivity (MDP)	1 Crab	(any DC source after $T_{obs} = 3$ year)
$3\,\sigma$, any DC source, 200–500 keV	0.1 Crab	2.4%
$T_{obs} = 3$ year	0.01 Crab	23.6%
GRB sensitivity ($5\,\sigma$)		$\sim 10^{-6}$ erg/cm^2
Timing		1 μsec relative, 1 ms absolute
Laue Lens Optic (^{56}Co line from SN1a)		
Energy range		800–900 keV
Spectral resolution		0.2–1% FWHM
Field of view / Angular resolution		5 arcmin / 1 arcmin
narrow line sensitivity (dE = 3%, $T_{obs} = 10^6$ s)		$1.0{\cdot}10^{-6}$ ph·cm^{-2}·s^{-1}
broad line sensitivity (dE = 0.5%, $T_{obs} = 10^6$ s)		$1.8{\cdot}10^{-6}$ ph·cm^{-2}· s^{-1}
CMO: Coded Mask Optic (Galactic bulge high resolution imaging)		
Energy range		0.1–10 MeV
Spectral resolution (10 MeV–0.1 MeV)		0.2–1% FWHM
Field of view (f = 30 m–7 m)		2°12′–8°54′
Angular resolution (f = 30 m–7 m)		12′–54′
Continuum sensitivity (any DC source		
in the Galactic bulge, 1.5 year)	200 keV	$3.1{\cdot}10^{-2}$ ph·cm^{-2}·s^{-1} MeV^{-1}
	500 keV	$9.0{\cdot}10^{-5}$ ph·cm^{-2}·s^{-1} MeV^{-1}
	1 MeV	$3.1{\cdot}10^{-5}$ ph·cm^{-2}·s^{-1} MeV^{-1}
Narrow line sensitivity, $T_{obs} = 1.5$ year	511 keV	$4.9{\cdot}10^{-6}$ ph·cm^{-2}·s^{-1}
any DC source in the Galactic bulge	1809 keV	$2.6{\cdot}10^{-6}$ ph·cm^{-2}·s^{-1}
Polarization, $T_{obs} = 1.5$ year	1 Crab	0.4%
$3\,\sigma$, any DC source, 200–500 keV	0.1 Crab	4.5%
Timing		1 μsec relativ, 1 ms absolute

its nominal lifetime of 3 years is $\sim 10^{-6}$ ph cm^{-2} s^{-1} at 1 MeV for every γ-ray source in the sky.

The most promising instrument design for fulfilling the sensitivity and wide-field requirements set forth in the section above is a Compton telescope utilizing recent advances in semiconductor detector technologies. Such an instrument can achieve significant improvements over the COMPTEL [13] which pioneered this technique in the 1990s. A compact semiconductor Compton telescope contributes to meeting scientific requirements through the ability to image both discrete sources and diffuse emission over a wide field-of-view (100% sky simultaneously), as well as the ability to perform simultaneous imaging and spectroscopy of line and continuum emission over a broad energy range (0.1–10 MeV). Among modern-day Compton detector technologies, Germanium provides the highest spectral resolution, crucial to understanding source dynamics via Doppler shifts and/or broadening of nuclear lines from radioactive decays or positron annihilation. Germanium also has a moderate Z—low enough to allow significant Compton scatters, but high enough to stop the photons in the instrument once they scatter.

Instrument conceptual design and key characteristics The baseline for DUAL's All-Sky Compton Imager (ASCI) is a stack of 45 highly segmented high-purity germanium (HPGe) detectors operating at cryogenic temperature, which combines the best performances to achieve the science objectives: **high detection efficiency** over a **large field of view**, **excellent spatial resolution** and **high spectral resolution**. The proposed technology and detector configuration have been studied in a close collaboration by CESR, Canberra France (HPGe detector manufacturer) and UC Berkeley. Figure 8 shows the DUAL focal plane detector. The sensitive part consists of 5 layers of 9 double-sided strip detectors (DSSD) made of HPGe. The 45 detectors are mounted on supporting frames specifically designed to be light and compact in order to maximize the instrument detection efficiency. This cold stage is sealed in vacuum within the cryostat box, and thermally isolated with thermal shield and MLI blankets. The overall thickness of materials will be minimized in the forward and backward directions (detector symmetry axis) so that shielding and scattering effects for incident γ-rays are limited.

Germanium strip detectors Each HPGe detector module has an active area of 100 × 100 mm^2 and a thickness of 15 mm, this large size is allowed by the extraction lengthwise from large grown HPGe crystals. The orthogonal X-Y strips on the two electrodes will be separated with a pitch of 2 mm and surrounded by a 1 mm thick guard ring. The double sided X-Y strip configuration is widely and exclusively used in applications using high resolution Compton imaging. It allows both excellent energy and position resolution when the full

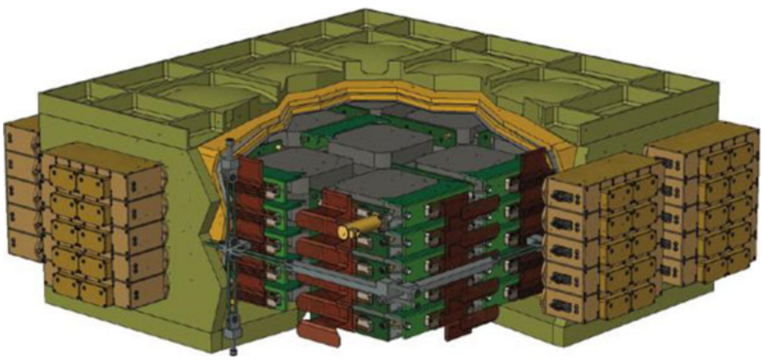


Fig. 8 The ASCI instrument

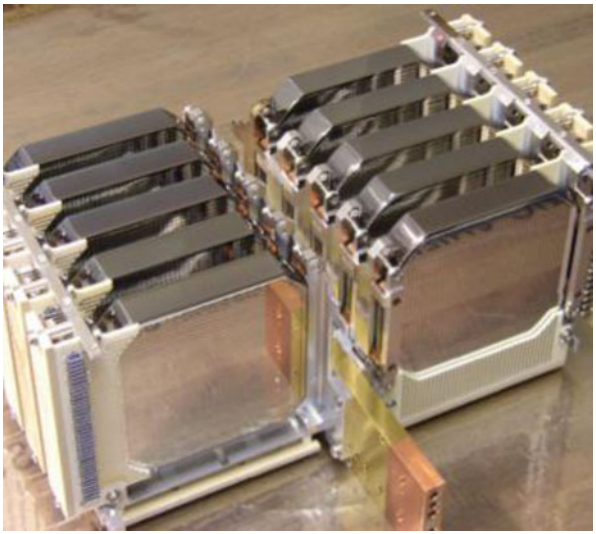
Table 4 Comparison of DUAL and NCT GeDs

GeD/ parameter	DUAL	NCT
Strip pitch	2.00 mm	2.00 mm
Strip gap	0.25 mm	0.25 mm
Individual detector dimensions	100×100 mm^2	74×74 mm^2
	15 mm	15 mm
Guard ring thickness	1 mm	2 mm
Spectral resolution		
(FWHM) @ 662 keV < 0.1 MeV (noise limit)	1.6 keV	1.6 keV
	2.1 keV	2.1 keV
Depth res. (FWHM)	0.4 mm	0.4 mm
Position resolution	1.6 mm^3	1.6 mm^3
Spectroscopy threshold	10 keV	12 keV
Depth threshold	25 keV	40 keV
Total # strip channels	4500	912
Instrument volume	6750 cm^3	972 mm^3

potential of signal processing is used (i.e. timing and pulse shape analysis on all the channels simultaneously, [12]). The expected position resolution for a γ-ray interaction within the HPGe detector is 1.6 mm^3. Table 4 summarizes the main performance parameters for such HPGe strip detectors, comparing them with the Ge-strip detectors of the Nuclear Compton Telescope (NCT, Fig. 9), a balloon telescope that has successfully flown and validated the entire proposed detector technology.

The design of the DUAL detector modules is based on existing HPGe strip detectors already manufactured in the past by Canberra for γ-ray tracking and imaging applications. It relies in particular on robust processes such as thin contact and passivation technologies developed in the last decade. All the

Fig. 9 The Ge-strip detectors of NCT



detectors, except the central position in the front layer, will be made the same in terms of shaping, surface process, mounting on the supporting frame, wire bonding and connection to flex ribbon cables.

The central detector in the front layer will be designed with an inner hole in order to allow γ-rays from the lens to hit directly the second layer; this configuration presents the best detection efficiency for the focused γ-rays. This central front detector will work the same way as for others, the strips in two parts from each side of the inner hole will be wire bonded together to create a single strip electrically.

Electronics A photon interacting in one of the HPGe detectors generates charge pulses on the corresponding X and Y strips (strip ID corresponding to the interaction location), which are collected and processed by the electronic subsystem. Each detector strip requires a compact, low power signal processing chain. Because of the large number of strips (100 per detector incl. guard ring), it will be necessary to use an application specific integrated circuit (ASIC).

The front-end electronics to read out the 4500 signal channels from detector strips is located in boxes mounted on the sides of the cryostat assembly and directly connected to the signal feedthroughs. The front-end electronics consists of a low power ASIC that already implements the first stage analog circuitry, as opposed to surface-mount components due to the large number of readouts and the mass and power constraints of a satellite. Each ASIC signal channel consists of a charge sensitive preamplifier, followed in parallel with a slow shaper and analog-to-digital converter for energy measurements and a fast shaper and comparator combined with a 100 MHz-clocked counter for timing measurements.

The proposed readout chip will have 50 channels. Each channel consists of a charge preamplifier followed by two shaping amplifier to achieve the required energy and timing resolution. Initial analyses show that a 150–200e rms noise, 2–3 ns rms timing resolution and a fast trigger threshold of 15 keV (threshold for depth determination) is feasible. A Wilkinson 12-bit ADC will digitize the analog signal. A digital block will take care of storing and reading out the data. The estimated power consumption is 6 mW/channel. The proposed technology for the integration is a commercial 0.25 μm mixed mode CMOS. A single Detector Interface Board (DIB) per detector will interface with the two ASICs for that detector. An FPGA on each DIB will control the digital data acquisition process from the ASICs, control threshold levels, and pass data to the instrument Data Control Board (DCB). Both DIBs and DCB are part of the IDPU, forming the interface between the instrument and S/C bus.

Radiation damage HPGe detectors in space are sensitive to cosmic ray bombardment. This typically causes hole traps and degrades the energy resolution obtained from both electrodes of the detector. Although concerning mainly coaxial detectors, extensive studies were performed in the past based on accelerator tests and on flown detectors such as INTEGRAL/SPI, and showed that radiation damage is minimized by maintaining the detectors below typically 85 K (avoiding warm-ups above 100 K), and that annealing the detectors for several hours at temperatures up to 100°C allows to recover significantly the initial energy resolution. In the case of DUAL detectors with a planar configuration, radiation damage will affect charge collection and energy resolution with much less importance as on coaxial detectors due to the small pixel effect. Moreover, unlike coaxial detectors, the choice of n-type instead of p-type HPGe crystals does not matter given the electric field and charge collection path of planar configuration. We believe that annealing will not be necessary during the primary 3 + 1 year DUAL lifetime; however, the ability to anneal the detectors to correct significant radiation damage will be studied during the assessment phase.

Specific interface requirements The 45 DUAL detectors are housed in a single vacuum cryostat, which will hold the HPGe detectors below 85 K for optimal performance. The cryostat design builds off of experience gained by Canberra on several projects like multiple detector cryostats for nuclear physics and space projects like INTEGRAL/SPI. Each layer of 9 detectors is mounted in its own supporting frame that is linked to a common cold finger structure. The five detector layers are fixed together to form the detector box, with dimensions $350 \times 350 \times 175$ mm^3.

The cryostat will have an intermediate-temperature shield between the detectors and the cryostat wall, enveloped on both sides by Teflon-based MLI blankets, optimizing cooler power usage. The cryostat is designed to hold 45 detectors, with 4550 signal feedthroughs (4500 strip signals, 45 high voltage, temperature sensors and ground cables). Despite the large number of signal leads, the use of Kapton-foil flex-circuits for the signal keep the overall thermal leakage through the signal leads comparable to the radiative thermal load for a total heat-lift requirement of 2.3 W from the cold stage and 4.0 W from the intermediate stage (Table 5). The entire cryostat assembly will be enclosed in a set of two thin IR radiation shields. With the thermally stable L2 orbit facilitating passive cooling, and considering the above heat loads, a radiator of 1.5–2 m^2 is a straightforward (at the cold stage, a radiator evacuates about 1.7 W/m^2, at the intermediate stage it evacuates $\sim$20 W/m^2), especially since this surface corresponds to the size of the “flap” on the ASCI platform (see Fig. 19) and which is required for balancing the radiation pressure with respect to the S/C. While passive cooling seemed to be an obvious choice for the baseline of the present document, a tradeoff will be lead during the assessment phase to validate this choice over the use of a small cryocooler, such as the Large Pulse Tube Cooler (LPTC) of Air Liquide Advanced Technology Division (AL/DTA) which provides adequate cooling power for a mass of only 5.5 kg.

Heritage Germanium detectors have flown on several space missions during the last two decades INTEGRAL/SPI, Mars Odyssey / GRS, RHESSI, KAGUYA/GRS, MESSENGER/GRS, etc. Canberra France not only manufactured a large fraction of those spaceborne HPGe detectors, but also played

Table 5 Thermal path way analysis for DUAL detector cryostat

Cold stage temperature [K]			77
Intermediate stage temperature [K]			150
Cold stage (detector box)	Support	Lin [W]	-1.5
		Rad [W]	0
	Ribbon Cable	Lin [W]	-0.7
		Rad [W]	0.02
	Shield	Lin [W]	0
		Rad [W]	-0.1
Intermediate stage	Detector box	Lin [W]	0
		Rad [W]	0.07
	Support	Lin [W]	0
		Rad [W]	0.30
	Ribbon cable	Lin [W]	-2.6
		Rad [W]	0.73
	Sink	Lin [W]	0
		Rad [W]	-2.5
Totals		Lin [W]	-4.8
		Rad [W]	-1.6
		All [W]	- 6.3
Cold stage cryo load [W]			-2.3
Intermediate stage cryo load [W]			-4.0
Total cryo load [W]			- 6.3

a leading role in developing key technologies for HPGe detectors, such as encapsulation and segmentation [8]. A design very similar to DUAL has already been realized the NCT instrument of for UCB/SSL Berkeley. NCT's HPGe strip detectors have been tested on stratospheric balloon flights; on its 2005 flight NCT has successfully detected and imaged the Crab Nebula [1] (Table 6).

Table 6 Mass and volume resources of the ASCI

	Mass [kg]	Cont.	Maturemass	Power [W]	Cont.	Mature Power
Ge detectors	35.9	10%	39.5	–	–	–
Mounting & contact boards	4.1	20%	4.9	–	–	–
Cryostat, cold fingers, structure, MLI	8.8	20%	10.6	–	–	–
Front-end/ASIC boxes & connectors	5.0	20%	6.0	16.2	20%	19.4
IDPU incl housing	9.3	20%	11.2	–	–	–
DIBs	–	–	–	16.2	20%	19.4
DCB & PCB	–	–	–	4.0	20%	4.8
Instrument Power Conv. & Controller	1.4	20%	1.7	16.7	20%	20.0
Plastic—housing, mounting, readout	6.0	20%	7.2	8	20%	9.6
HV power supplies and filters	5.4	20%	6.5	21.2	20%	25.4
Radiator Panels	12.0	20%	14.4	–	–	–
Harness	7.9	20%	9.5	–	–	–
TOTAL	95.8		111.5	82.3		98.8

Critical issues The critical issues so far identified for the detector system concern: The choice for cooling solution: Dedicated efforts should be performed in R&D phase to decide between passive and active cooling solutions. The manufacturing yield for large size HPGe detectors: Although the extraction of a planar strip detector lengthwise from the HPGe grown crystal has already been done by Canberra and Berkeley labs [11], it implies restrictions on the crystal specification, and has an important impact on detector manufacturing yields and costs. R&D efforts should be developed in the assessment phase in order to optimize crystal growth and process for the required large size. The feasibility of the central detector in the front layer: The presence of the hole in this detector presents some risks on its reliability and will require some developments in the manufacturing processes. In any case, a backup solution with a normal detector (no hole) may be chosen without compromising the science objectives. ASIC development: ASICs meeting both the spectral resolution and timing resolution requirements for the HPGe detectors have been developed for other Si and CZT detectors with similar strip capacitances, though these features have yet to be integrated into a single ASIC for HPGe detectors. R&D efforts should be developed in the assessment phase in order to identify any outstanding challenges for moving forward with flight ASIC design and fabrication.

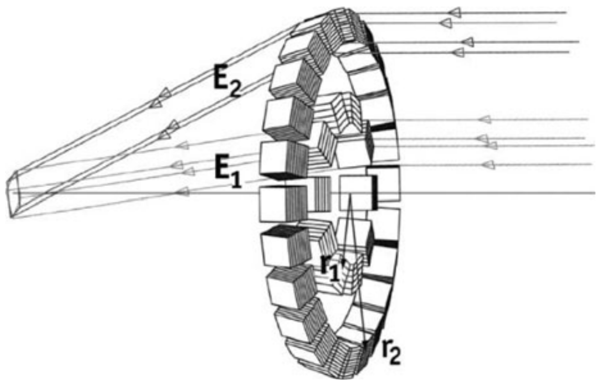
3.3 Laue lens optic (LLO)

A Laue lens offers the unique possibility of concentrating gamma rays from a large collection area onto a small focal spot. The dramatically improved SNR leads to outstanding sensitivity. DUAL's Laue Lens Optic (LLO) focuses in the 800 keV–900 keV energy band, relevant for the detection of the 56Co line of SN1a. It is composed of 5800 crystals glued onto a CeSiC monolithic substrate. The total weight amounts to 80 kg, the outer diameter is 98 cm.

Instrument conceptual design and key characteristics The LLO consists in a broad-band gamma-ray lens based on the principle of Laue diffraction of photons in mosaic crystals. Each crystal can be considered as a little mirror that deviates gamma rays through Bragg reflection. Each crystal diffracts an energy band proportional to its mosaic spread (also called mosaicity). The crystals are arranged in concentric rings, symmetrical with respect to the optical axis. A broad-band gamma-ray lens can be obtained through a careful selection of the inclination angle on each of the rings, which allows a continuous energy band to be covered. Since large energies E_1 imply smaller diffraction angles θ, crystals diffracting large energies are located on the inner rings of the lens. Conversely, smaller energies E_2 imply larger diffraction angles and consequently the corresponding crystals are located on the outer rings (see Fig. 10).

The LLO is composed of 5800 crystals arranged in 32 concentric rings, each ring being populated by identical crystals. The characteristics of the LLO are presented in Table 7. The crystals are glued onto a CeSiC monolithic substrate

Fig. 10 Principle of the gamma-ray lens payload



that combines many properties. Beside being space qualified, this material have excellent mechanical stability and thermal conductivity, is lightweight and have an absorption lower than 6% at 850 keV (for a thickness of 3 mm). The effective area of the LLO is shown in Fig. 11. It peaks at 340 cm^2 at 847 keV. At the focus, 62% of the signal is concentrated in a disc of 7 mm of radius (1.54 cm^2), which represents a concentration factor of ~220. Previous theoretical studies together with experimental work (see eg. Curado da Silva et al. [5]) has confirmed that the polarization status of a beam is not changed after Laue diffraction at small angles ($<1°$).

Measurement technique and pointing requirement SN1a are first discovered in visible light, most of the time within a few days after their explosion. At the time when the LLO will point towards them, they are point sources of known position. The observation strategy will consist in multiple (typically 4) pointed observations of 10^6 s, starting a few days after their discovery and distributed over about 6 months. The requirement for the lens pointing is ±20 arcsec, ±10 arcsec being the goal.

Interface and thermal stability The LLO is attached to the spacecraft. The thermal stability requirement derives from the crystals that should keep their orientation within ±10 arcsec with respect to the lens optical axis. During the MAX pre-phase A study at CNES, the thermal control of the Laue lens was investigated [9]. It showed that a cocoon of multilayer insulator (MLI)

Table 7 Characteristics of the LLO

Parameter	Value	Parameter	Value
Focal length (m)	30.0	Mass of crystals (kg)	61.0
Inner radius (cm)	12.85	Crystals size (mm^2)	10 × 10
Outer radius (cm)	48.50	Crystals thickness (mm)	5.1–12.0
Crystal materials	Rh, Ag, Pb, Cu, Ge	Crystals mosaicity (″)	45
Number of crystals	5800	Crystalsinter-spacing (mm)	0.5

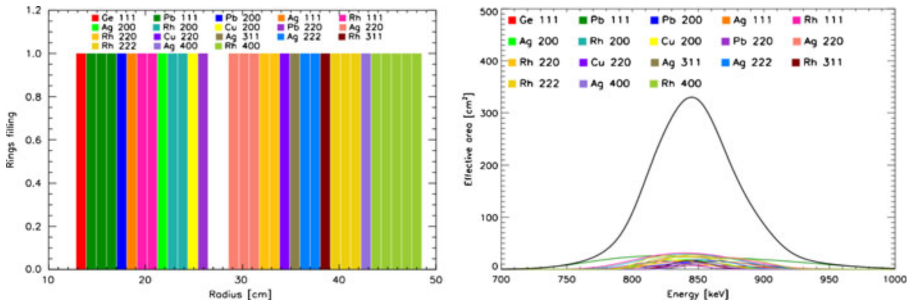


Fig. 11 *Right*: The color strips represent the crystal and reflection used for each ring. The lens is composed of the following crystals: 3193 Rh, 1662 Ag, 521 Pb, 348 Cu and 76 Ge. *Left*: Effective area of the LLO. This calculation assumes crystals oriented within 10 arcsec of their nominal angle (1 sigma, Gaussian distribution), and takes into account the absorption of the substrate (3 mm of CeSiC). The crystals are modeled using Darwin's model of mosaic crystals fed with experimentally determined parameters [3]

surrounding the lens, added to a few heaters and thermistors on the lens structure are sufficient to limit to 2°C the thermal gradient across the lens for any sun exposition, which in the case of MAX would insure a crystal disorientation lower than 10 arcsec. The proposed LLO has a much simpler and smaller structure that MAX's, so it is believed that the thermal gradient permitted might be higher than 2°C.

Current heritage and technology readiness level The proposed lens is based on the experience gained in the Laue lens R&D work conducted during the last decade at CESR (France), UNIFE (Italy), and Argonne National Lab (USA), which culminated so far in the first detection of a gamma-ray source (the Crab nebula) using a gamma-ray lens during a stratospheric balloon flight (CNES funded CLAIRE project, [15]). We also benefit from the experience gained during the CNES assessment study of MAX [6], the ESA Technical Reference Study on GRL [4] and the GRI study proposed to ESA in the framework of CV07 [10]. Technologically, the LLO can be split into 3 components: the crystals, their assembly onto a substrate, and the substrate (which all benefited from the recent CNES funded R&D, R-S09/SU-0002-025 R&T, R-S06/SU-0002-025 R&T and R-S06/SU-0002-026 R&T).

Crystals The crystals used for the LLO (mainly Rh, Ag, Pb) have proved to exist with the required mosaicity [3]. They are currently being investigated by our collaboration in a NASA-founded study aiming to demonstrate their availability in an industrial pattern. The complementary crystals (Ge, Cu) have already been used on Laue lens prototypes developed by CNES/CESR in France [15] and ASI/University of Ferrara in Italy [7], and proved to be suitable for the realization of a Laue lens. Especially Cu was investigated in the framework of the successful ESA-founded Gamma–Ray Optics Development activity (ESTEC contract No. 20357/07/NL/NR). The most critical issue concerns Pb crystals, which might be difficult to obtain in large quantity (521 crystals are necessary). An alternative option could consist in using gold instead, which already proved to be available with suitable mosaicity [2] and is easier to cut and manipulate.

Assembly method Three different assembly methods have been investigated during the past 10 years in France and Italy. In particular, the latest investigated in a CESR/TAS collaboration (CNES contract n°70662/00 with TAS Cannes, ref DCT/SA/AB n°07-3202) led to the realization of a prototype module that showed outstanding results with 10 arcsec orientation accuracy obtained on several crystals. This module successfully underwent vibration and thermo-vacuum cycles tests. The requirements on the LLO structure do not show any particular difficulty as CeSiC large structure have already be proven in space (Fig. 12).

3.4 The coded mask optic

DUAL's Coded Mask Optic (CMO) is adding high angular resolution to the All-Sky Compton Imager in a single region of highest importance for gamma-ray astronomy: the Galactic Centre bulge. Coded aperture systems—consisting of masks or collimators—have been successfully used in high-energy astronomy for over 20 years. Especially INTEGRAL has shown that it is possible to image with high efficiency both point and diffuse sources. Using the spatial modulation provided by the coded mask in combination with an optimized pointing strategy, the information on the source fluxes from different directions in the Field-of-View can be reconstructed and the systematic errors minimized.

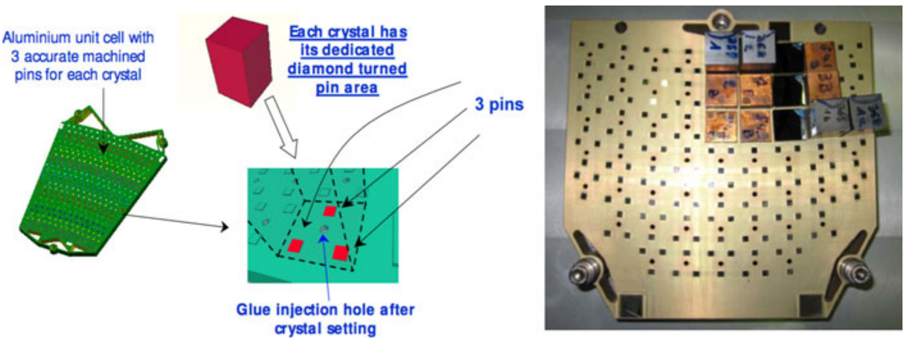


Fig. 12 Assembly method developed by Thales Alenia Space in the framework of the CNES contract R-S06/SU-0002-026 R&T. Thirteen crystals of different materials and thicknesses were fixed on the prototype module shown on the right hand side. The module was recently tested in vibration and thermo-vacuum cycles, without any measurable effect on the crystals quality and orientation

Instrument conceptual design and key characteristics The CMO will use the ASCI as focal plane detector placed 30 m apart. Its size is physically limited by volume and mass constraints. The design foresees the mask assembly to be 1 m^2 in size and the use of a pattern of tungsten blocks with thickness 9 mm for spatial multiplexing of the gamma rays within a FoV of 2.5° full-width-at zero-response. Although the mask is modulating source photons over the entire energy range of the ASCI (100 keV–10 MeV), the CMO is optimized for sensitivity at 511 keV, in order to be able to map the diffuse emission from the Bulge with an accuracy better than one order of magnitude than the ASCI telescope resolution. With an angular resolution of 12′ (54′ at a focal distances of 7 m) the CMO can measure the possible point source contribution at 511 keV when operating at the longer baseline, and map the Galactic Bulge diffuse emission for shorter mask-detector distance.

In the latter case, the FoV is 8 × 8° for >50% coded area, i.e. significantly larger than the ASCI ARM and it is then possible by filtering photon directions in the deconvolution or fitting process, to improve the image capability and the SNR (by about a factor of 2). The mask pixel size chosen is 11.1 cm and the open fraction of the mask is 50%. In order to avoid periodicities in the mask pattern that would cause ambiguities in the reconstruction of the source fluxes, we have chosen a pseudo-random matrix of 9 × 9 elements as mask pattern. The mask will be placed on a carbon fiber supporting structure made of two flat panels and a CFRP supporting grid or honeycomb. Supporting the mask does not present particular risks and can be considered standard in view of the successful on INTEGRAL, which has a factor ∼2 heavier masks.

Performance assessment with respect to science objectives The finite spatial resolution of the ASCI being ∼20 times higher than the CMO element size, there will be no loss of sensitivity due to the discretization of the spatial information. The thickness of the tungsten elements provides an opacity of 90% at 500 keV and 53% at 2 MeV. In order to map the diffuse emission of the Galactic Bulge, the optimal configuration is the one at shorter distance (7 m), for which it is possible to use the Compton event selection. However, should this option be not viable, the mapping of the 511 keV emission of the Bulge is still feasible at 30 m by a survey of a ∼50 square degrees region with a grid of pointings. In this case we exploit the modulation provided by the mask as a whole and the sensitivity is enough to provide a ∼2° resolution map. The angular resolution of 12′ at 30 m is sufficient to exclude point sources contribution at 511 keV or conversely, to identify and locate them at a level of accuracy appropriate for identification.

An outstanding possibility could be to use a hybrid mask (two spatial scales) to provide fine imaging at lower energies, provided the ASCI has extended range down to ∼20 keV. In this case it should be possible to reach an angular resolution as low as 30″ by adding a thin (∼0.5 mm) tungsten layer on top of the coarse mask. The additional tungsten layer would not affect the sensitivity at 511 keV for an operational range of ∼20–300 keV.

The CMO will have a total mass of 97 kg, with 9 kg for the supporting structure (w/o contingency). For the W, a margin of 5% can be assumed. The required volume about 50,000 cm^3. No special mode or on-board data processing is required for the operation of the ASCI with the coded mask, if the telemetry is on an event-by-event basis. The accuracy required by the CMO on the attitude and CMO-ASCI relative alignment is 0.2 arcmin.

3.5 The DUAL mast

A hybrid structure to support the ASCI at a distance of 30 m is proposed as an alternative to traditional rigid structures and formation flying technologies. For the relaxed requirements of DUAL (essentially the focal spot has to stay on the 30 cm wide detector), such a concept is advantageous in terms of mass and cost when compared with other solutions.

Instrument conceptual design and key characteristics The Collapsible Tube Mast (CTM) is a concept already developed and flown by SENER as a deployment element used for space payloads. Stored in a box like a rolled stripe, once deployed outside the box, its section acquires a lentil shape that is stiff enough to be used as a mast with a mass on the other extreme. It is manufactured in two different materials (Carbon Fiber and Copper-Beryllium) and five different sizes with increased masses and stiffness (DUAL foresees caliber 5: i.e. a section of 13 $\times$ 194 mm and a mass of 180 g/m (CFRP) or 1070 g/m (CuBe). The proposed hybrid concept is based on the use of CTMs for the deployment and separation of the detector and the lens. Two configurations with 3 CTMs arranged in a equilateral triangular shape have been analysed, each with one of the different existing material options: Carbon Fiber and Copper-Beryllium. Carbon Fiber has a lower mass per unit length but is less rigid whereas the Copper-Beryllium is exactly the opposite and offers a higher rigidity but with a higher mass. For both structural configurations, a control system have been analysed and designed, leading to feasible features, where special care has been taken to address the issue of the inherent structural flexibility of the system. A future trade-off will be performed where a more in-depth analysis will be performed regarding the stability and controllability with a large emphasis on the necessary robustness properties.

Performance assessment and pointing and alignment requirements The main requirement for the mast is to maintain the detector soft spot (Ø 3 cm) in the focal spot of the LLO at a distance of 30 $\pm$ 0.1 m—the minimum requirement is to keep the 30 cm wide detector in the lens beam. For the observation with the LLO and CMO, the spacecraft maintains an inertial pointing towards the source, requiring an absolute accuracy of 20 arcsec for the lens only. This fine pointing is potentially jeopardized by the modes generated by the mast. SENER has therefore performed a dedicated modal analysis of the 3-CTM configuration with the detector mass at one end. Eigenfrequencies and effective masses for translation and rotation of the flexible modes were computed, leading to the following flexible modes frequencies (1st mode): 0.041 Hz (Carbon fiber) and 0.054 Hz (Copper-Beryllium). It has been shown (see the results of the analysis on http://dual.cesr.fr/M3/mast) that the structural flexibility and its associated deformations do not impose a fundamental limitation on the control design feasibility.

The 3 CTMs and containers have a total mass of 61.2 kg (without contingency). Single CTMs are already flight qualified, and specific actions will be developed during the assessment phase to address the synchronization issue—i.e. simultaneous deployment of the three CTMs.

Possible alternative deployable structure are rigid masts such as the ADAM (Able/ATK) or the Self Deploying Tube Structure (SDTS) currently being developed by Astrium in the UK. The ADAM mast has a very long record of success in space—in the case of an US involvement in DUAL, this mast would represent a substantial contribution. An ADAM mast will be used in 2012 as an optical bench with in the NuStar X-ray mission.

ASTRIUM's SDTS concept uses a series of panels attached via tape spring hinges which are folded flat in the stowed configuration to provide a packing efficiency of $\sim$ 1:20. The deployment is totally passive, with motion achieved using the stored energy within the tape springs. Controlled deployment can be achieved through one of a number of damping systems. Astrium has demonstrated that this type of structure can provide excellent deployed stiffness ($>$2 Hz) out to focal lengths of up to 80 m. It can also be constructed entirely of carbon composite so will be both thermally stable and mass efficient. Astrium's preliminary breadboard has resulted in a current TRL of 3; the technology is expected to reach TRL 4 by 2012, in line with the ESA TRL requirements for Cosmic Vision

A significant scientific benefit would consist in the possibility of retracting the mast to change its length (e.g. from 30 m to 7 m for observation with the CMO). Flight qualification will be required but this possibility is technically feasible and will be addressed in the assessment phase. The implementation of the focal length reduction of the telescope to 7 to 15 m would be performed

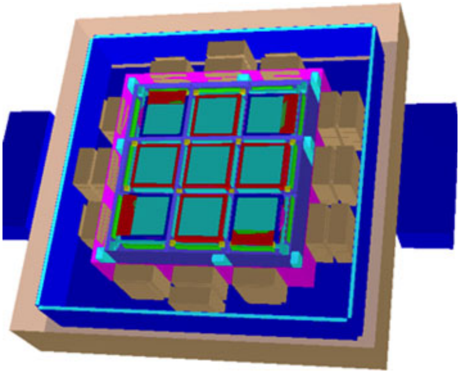


Fig. 13 ASCI Simulation mass model

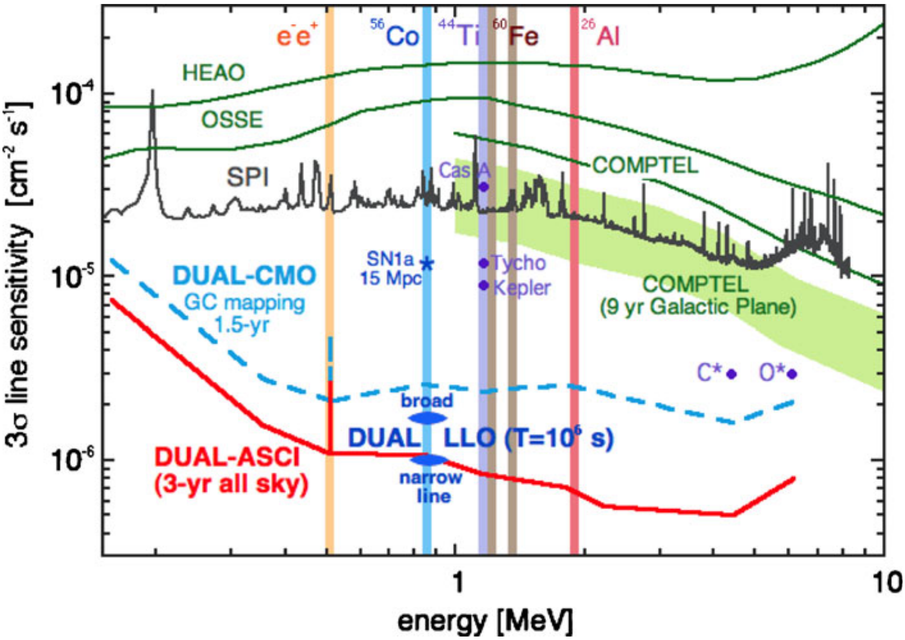


Fig. 14 DUAL line sensitivity after its 3 years of continuous sky survey, the sensitivity achieved by the All-Sky Compton Imager (ASCI) for any source on the sky is an improvement by a factor of 30 with respect to previous missions. The same spectacular improvement is achieved by the Laue-Lens Optic (LLO) in 10^6s during deep observations of the broad ^{56}Co line from SNIa. The Coded-Mask Optic (CMO) provides high angular resolution imaging (10′–40′) in the Galactic Bulge region (FOV 2°–8°)

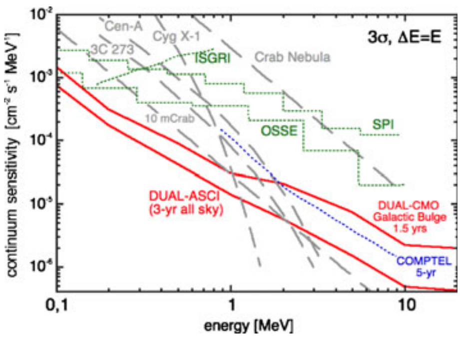


Fig. 15 DUAL continuum sensitivities: While not specifically designed as a broad-continuum instrument, the All-Sky Compton Imager ASCI will achieve outstanding sensitivities, and perform spectroscopic studies of a wide variety of high energy sources on the entire sky. Furthermore, the coded mask optics (CMO) provides high angular resolution imaging (12′–54′) in the Galactic Bulge region (FOV 2°–8°). For comparison, the extrapolated spectra of selected point sources are show, along with the "pointed" sensitivities of OSSE, ISGRI, SPI ($T_{obs} = 10^6$ s) and the sensitivity of COMPTEL's 5 year survey

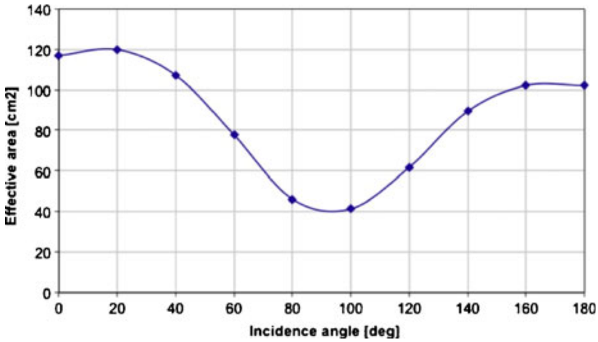


Fig. 16 ASCI Effective area at 511 keV, as a function of incidence angle

at the end of the mission for additional mask-based observations, which would imply an added bonus to the already performed scientific mission.

3.6 Performance assessment and science objectives

The ASCI, LLO and CMO payload performances have been evaluated by dedicated simulation software. The critical performance parameters for these payloads are the expected effective area and focal spot characteristics as function of energy. For the ASCI, the most critical properties are the instrumental background and detection efficiency (which is limiting the sensitivity) and the spectral resolution (which is limiting the energy resolution). An accurate mass model that includes passive material in the detector and its surroundings, true energy thresholds and energy and position measurement accuracy, and a roughly accurate S/C bus mass and position are crucial to this modeling. Figure 13 shows the mass model used for ASCI simulations, which were performed using the MEGAlib package [18]. Care has been taken to accurately include all passive materials close to the detector. The simulated background environment includes cosmic diffuse photons, cosmic-ray protons, electrons,

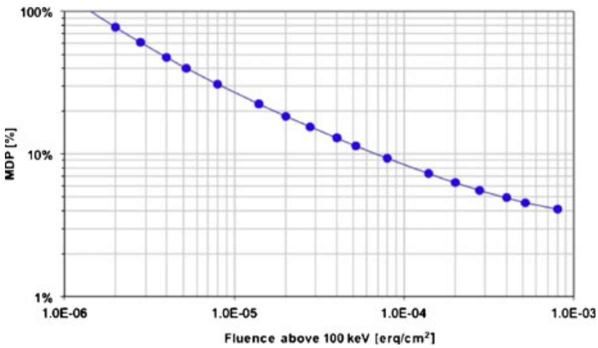


Fig. 17 ASCI Minimum detectable polarisation (MDP) for a gamma-ray burst characterized by broken power-law with a single break ($a = -1.0$, $b = -2.5$, break: 150 keV)

and positrons, calculated using the MEGAlib environment tools. MEGAlib (and its predecessor MGGPOD) has been successfully applied to modeling the instrumental backgrounds of the TGRS, SPI, and RHESSI instruments, and the NCT balloon payload.

The relevant DUAL performances are summarized in Table 3 and in Figs. 14, 15, 16 and 17.

4 Spacecraft

The DUAL payloads consists of two optics modules, the LLO and the CMO that are coded mask deployed on the S/C after launch, and a detector (ASCI) on top of a 30 m deployable mast. The following sections describe the proposed spacecraft design.

4.1 Overall design

For the DUAL spacecraft we propose the use of a Thales Alenia Space PROTEUS MARK 2 satellite class, a multi-purpose platform presently under development in the frame of GOKTURK program. This platform is issued from PROTEUS mark 1 platform, which is flight-proven with the successful launch of the JASON-1, JASON-2, CALYPSO, SMOS and COROT satellites. The robust and reliable PROTEUS structure is composed of an aluminum rod assembly forming a cube (1.25 m long) stiffened by sandwich panels. It acts as primary structure and guarantees the transfer of main loads from payload to launcher through a fully machined aluminum frame. The PROTEUS MARK 2 structure is compliant with present estimated maximal payload mass of 404 Kg. Adaptations will however have to be brought to this platform to deal with L2-orbit constraints, which are described hereafter (Figs. 18 and 19).

Attitude and orbit control and reaction control system requirements The PROTEUS MARK 2 AOCS provides a reliable and simple safe mode, an intermediate attitude acquisition mode, and a nominal operational mode based on stellar sensing and reaction wheels for actuation. To ensure a good pointing accuracy, the 3 star trackers heads have been placed on the LAUE lens support plate. During the pre-assessment, this preliminary design will be re-assessed and traded against other accommodation possibilities.

The attitude is controlled through four reaction wheels with 20 Nms angular momentum capacity each. The sizing of the upper flap and of the solar arrays has been done to balance the differential solar radiation pressure at a maximum. The 20 Nms wheel capacity should thus be enough to interspace wheels de-saturations in compliance with Payload pointing duration requirements. It will have to be refined during the pre-assessment phase.

The orbit control and maintenance is done through a propulsion subsystem based on Hydrazine (N_2H_4) with 16 thrusters and a 50 kg tank. The exact thruster topology and thrust level will be thoroughly studied and determined

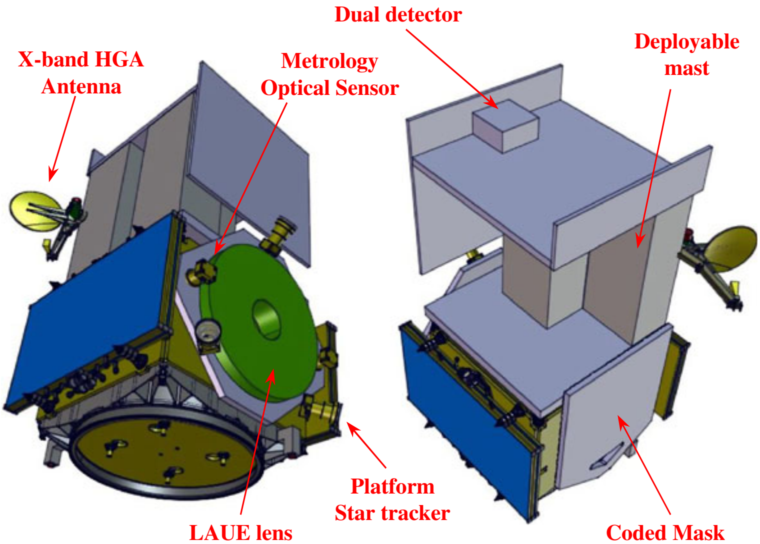
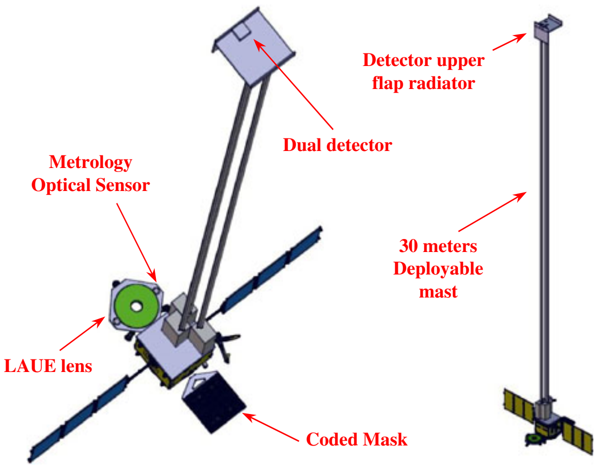


Fig. 18 DUAL in folded configuration

during the pre-assessment phase to deal with the 30 m mast constraints. L2-orbit specificity will lead to modify the PROTEUS MARK 2 AOCS, by removing the 2 magnetometers and the 3 Magnetic bars used for wheels de-saturation. The de-saturation maneuvers will thus be performed with the thrusters and optimized with payload re-pointing strategy. Control laws of nominal modes and safe modes will also be have to be adapted to the specific DUAL configuration, with high inertia values and the low Eigen frequencies of the mast-detector assembly.

Fig. 19 DUAL in deployed configuration



Power management and distribution Standard GaAs Solar Arrays can be used on DUAL satellite since the Solar Flux in L2 position is very near from the flux encountered near the Earth. Considering the power budget provided in Table 8, four 1 m^2 GaAs panels deliver enough power for the platform and the payload with comfortable margins. However, 2 other dummy 1 m^2 panels have been added to equilibrate the Solar radiation pressure imbalance generated by the detector thermal flap located at the end of the mast. The battery sizing is mainly driven by the platform consumption during launch. After separation, the Solar Arrays are released and continuously deliver power to the Satellite during the cruise and in L2 position. As a consequence, battery size on DUAL satellite has been greatly lowered with respect to Low Earth Orbit (LEO) configuration of the PROTEUS MARK 2 platform. A Power Conditioning and Distribution Unit (PCDU) will manage the power share between the Solar Arrays and the battery, and will distribute this power to the platform and payload units.

Thermal control The passive thermal control uses only conventional and qualified components (radiators and MLI). The redundant active thermal control is based on a heating concept of regulation driven by the on-board computer. It can be noticed that L2 point induces a stable thermal environment, with no Earth albedo nor strong eclipse phases. As a consequence, the thermal control as described here above is suited to such conditions. A detailed thermal analysis of the detector will be performed during the pre-assessment phase to determine if the present passive thermal control (MLI, Sun shielding & radiator panel) is able to keep the detector at the required temperature in all operational conditions. If this is not the case, a cryo-cooler machine would be required at detector level. Considering present power margins, such a cooler would remain compatible with present platform design. It would however increase a little the global mass budget.

Table 8 DUAL system level mass and power budget

Sub-system	Mass (kg)				Power (W) max.
	Basic	Margin		Current	
AOCS/GNC	51	10%	5	56	53
TT&C	30	10%	3	33	156
Data handling	18	5%	1	19	67
EPS	80	10%	9	89	25
Propulsion including Hydrazine	59	10%	6	65	1
Thermal control	18	10%	2	20	115
Bus structure	151	10%	15	166	
Total service module budgets	407 kg		41 kg	448 kg	417 W
DUAL payload	337	20%	67	404	123
Total payload budgets	337 kg		67 kg	404 kg	123 W
Harness & PCU losses	39	10	4	43	21
System margins		20%	168	168	112
Total budgets (incl. margin)				1063 kg	673 W

On-board data handling The command & control sub-system is based on a centralized architecture and fully redundant. A central computer (SMU) controls the platform and the payload. The main CPU is an ERC32 processor to provide the DUAL satellite with the necessary mission autonomy. A mass memory is available within the SMU or in a dedicated unit, to allow satellite Housekeeping and Payload data storage between two Earth communication sessions. The TC&R subsystem provides an X-band ground link able to provide full duplex command, platform telemetry, payload data and ranging interfaces between the satellite and dedicated ground station according to ESA standards. The TC&R exhibits a high reliability thanks to its full redundancy. Two low-gain antennas ensure a permanent visibility with Earth ground stations for any satellite attitude. A mobile high-gain antenna is used in nominal conditions, providing a high download data rate and having enough degrees of freedom to deal with payload re-pointing needs.

Mission operations concept The mission operations for the DUAL mission will take place from ESA's European Space Operation Centre (ESOC). After Launch, ESOC will support the early IOT, the cruise to L2 point and the DUAL configuration setup.

Estimated overall resources The DUAL satellite system level mass and power budgets are summarized in Table 8. All sub-systems are inherited from the PROTEUS family. The Technology Readiness Level (TRL) for all proposed sub-systems in this study is high (>6).

Specific environmental constraints The environment encountered by DUAL satellite during the cruise to L2 and once arrived at the operational point, is less constraining than for LEO missions. Radiation fluxes are much lower and while Solar flux is equivalent, the Earth albedo is removed. Moreover, the Solar illumination is far less variable than for LEO due to L2 orbit stability. As a consequence, the same PROTEUS MARK 2 platform architecture can be reused, particularly concerning equipment shielding and thermal control concepts.

Special requirements Due to ASCI-LLO relative alignment requirements, a metrology system has been accommodated on the DUAL satellite. The proposed metrology is based on optical sensors with two redundant optical heads on the lens and targets on the detector. An actuation part will also be added to achieve the required alignment between the DUAL payload parts. The metrology architecture will be thoroughly studied during the pre-assessment phase, addressing different trade-offs on each part: for optical sensors, targets choice between power LEDS or corner cubes with laser illuminator installed on the lens, and for actuation part choice between a movable mast root or a Lens rotation through a 2-DOF actuator.

Current heritage and technology readiness level The DUAL satellite reuses the PROTEUS MARK 2 platform having a strong heritage from previous PROTEUS MARK 1 missions and studies. Few adaptations will be made to comply with L2-orbit specificities. The most important modifications will concern the AOCS software related to the DUAL satellite configuration with high inertia and low mast Eigen frequency. But associated modifications does not jeopardize the platform strong TRL. The TTC architecture will also be adapted, removing the S-band equipment and accommodating X-band equipment instead. All X-band parts foreseen for DUAL satellite have a high TRL. Only the mast will require a specific development, with a planned TRL of 5 in 2015.

Critical issues The mast development is the critical part of the platform, and should have an Eigen frequency high enough for AOCS commandability while having enough stiffness to deal with satellite repointing needs.

Science operations and archiving DUAL is a survey mission. The ASCI will perform continuous sensitive γ-ray spectroscopy and polarimetry observations of the complete sky. The LLO and the CMO will mostly point towards the galactic bulge or nearby SN1a for long periods of time (few weeks).

The mission planning is very simple. Every few weeks the optical axis of the satellite will be re-pointed towards a new direction. The sequence of these pointing will be defined by the project scientists with the advise of the DUAL users group, mostly triggered by the occurrence of nearby SN1a. There will be no announcement of opportunity for observation but target of opportunity proposals could be submitted at any time to the project scientists. After the initial PV/calibration phase, data will become immediately public.

The main mission data output is a list of reconstructed γ-ray events accumulated over the full mission, with timing, localisation, energy and polarisation information. The data analysis requires tools to perform the proper data selection, effective area and responses generation and finally to create sky images and source spectra. Events detected through the LLO and CMO will be treated specifically as the background rejection can be treated very efficiently in these cases.

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Appendix

Back-of-the-envelope estimate for the sensitivity improvement, comparing the SPI sensitivity with ASCI.

	mean $\hat{A}_{eff}$ at 1 MeV	T_{obs}	BGD at 1 MeV	Sensitivity gain
INTEGRAL/SPI	65 cm^2	10^6 s	~ 0.1 c/s·kev	
DUAL/ASCI	~ 51 cm^2	$9.5 \cdot 10^7$ s	$\sim 7.3 \cdot 10^{-3}$ c/s·kev	
Improvement ~ vasci/spi	0.88	9.7	3.7	32

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The DUAL Consortium

Peter von Ballmoos[1], Jose Alvarez[2], Nicolas Barrière[3], Steve Boggs[3], Andrei Bykov[4], Juan Manuel Del Cura Velayos[5], Filippo Frontera[6], Lorraine Hanlon[7], Margarita Hernanz[2], Emmanuel Hinglais[8], Jordi Isern[2], Pierre Jean[1], Jürgen Knödlseder[1], Lucien Kuiper[9], Mark Leising [10], Benoît Pirard[11], Jean-Pierre Prost[12], Rui M. Curado da Silva[13], Tadayuki Takahashi[14], John Tomsick[3], Roland Walter[15], Andreas Zoglauer[3]

[1]IRAP, 9 avenue du Colonel-Roche, F-31028 Toulouse, France
[2]IEEC/CSIC, Torre C5 Parell 2a Planta, 08193 Bellaterra, Barcelona, Spain
[3]Space Sciences Laboratory, University of California, 7 Gauss Way, Berkeley, CA 94720-7450, USA
[4]Ioffe Physical-Technical Institute, 26 Polytekhnicheskaya, 194021 St Petersburg, Russia

[5]Sener, Calle Severo Ochoa, 4, 28760 Tres Cantos, Madrid, Spain
[6]Universita di Ferrara, Via Savonarola, 9, 44121 Ferrara, Italy
[7]University College Dublin, Belfield, IE-Dublin 4, Ireland
[8]CNES, 18 Avenue Edouard Belin, 31401 Toulouse, France
[9]Netherland Institute for Space Research, Sorbonnelaan 2, NL-3584 Utrecht, The Netherlands
[10]Clemson University, 29634 Clemson, SC, USA
[11]Canberra, 1, Chemin Roseraie, 67380 Lingolsheim, France
[12]Thales Alenia Space, 100, Boulevard Midi, 06156 Cannes la Bocca, France
[13]LIP, Departamento de Física, Universidade de Coimbra, 3004-516 Coimbra, Portugal
[14]Institute of Space and Astronautical Science, Yoshinodai Sagamihara, 229-8510 Kanagawa, Japan
[15]Integral Science Data Center, 192, route de Vernier, CH-1214 Vernier, Geneva, Switzerland