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A DUAL mission for nuclear astrophysics

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ABSTRACT

Gamma-ray astronomy presents an extraordinary scientific potential for the study of the most powerful sources and the most violent events in the Universe. In order to take full advantage of this potential, the next generation of instrumentation for this domain will have to achieve an improvement in sensitivity over present technologies of at least an order of magnitude. The DUAL mission concept takes up this challenge in two complementary ways. While the Wide-Field Compton Telescope (WCT) accumulates data from the full γ-ray sky (100 keV–10 MeV) over the entire mission lifetime, the Laue-Lens Concentrator (LLC) focuses on ^{56}Co emission from SNe Ia (800–900 keV), collecting γ-rays from its large area crystal lens onto the WCT. A boom or two separated spacecraft flying in formation will maintain the gamma-ray optics and detector at the lens' focal distance. The sensitive gamma-ray spectroscopy that can be performed by DUAL addresses a wide range of fundamental astrophysical questions such as the life cycles of matter and the behaviour of matter under extreme conditions.

1. The case of nuclear gamma-ray astronomy

Gamma-ray observations unveil the most extreme conditions known in the Universe, 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 are able to create matter from pure light. These extreme conditions occur generally at the endpoints of stellar lives, where 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, 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 importance of understanding these extremes has been stressed in all major strategic plans for astronomy (see e.g. "Science Vision for European Astronomy" of ASTRONET, ESA's "Cosmic Vision", and the "Decadal Survey" in the US). The principal science themes for future gamma-ray astronomy have motivated various mission concept studies such as ACT [1], GRI [2], and GRIPS [3].

2. Mission requirements

The foremost need for the next generation gamma-ray mission is a significant improvement in sensitivity, by at least an order of magnitude with respect to existing instrumentation. The performance requirements for gamma-ray line spectroscopy can be illustrated by comparing observed or anticipated source fluxes with the observed or expected angular scales: Fig. 1 indicates that emissions with a wide range of angular and spectral extent are expected, 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 gamma-ray spectroscopy span through 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.

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 the narrow 511 keV line – or because they are relatively close by as the nucleosynthesis sites in the local spiral arm (^{26}Al in the Vela and Cygnus region). An instrument that is adequate for this kind of objectives should provide a narrow line sensitivity of several 10^{-6} ph cm^{-2} s^{-1}, a wide field of view and an angular

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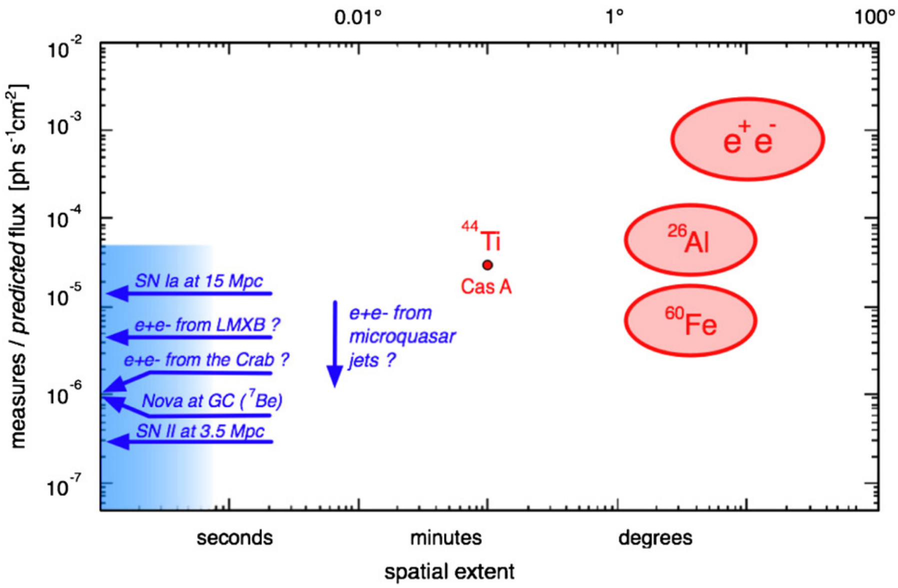

Fig. 1. A future spectroscopy mission has to face emissions with a wide range of angular extents, and with intensities different by several orders of magnitude: the requirements naturally can be divided into two subsets: a requirement for medium-sensitivity large-scale exposures, and very deep pointed observations.

resolution in the degree range. Such a profile typically corresponds to the performance of Wide-Field Compton Telescope.

In the area at the lower left of Fig. 1 various objects are predicted – such as supernovae, galactic novae, LMXB, pulsars … These sources will have small angular diameters but very low fluxes – mostly because such objects are relatively rare and therefore are more likely to occur at large distances. In order to cover the objectives in this area, deep observations of selected narrow-field targets have to be performed with a telescope of unprecedented sensitivity.

3. The DUAL mission

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 a Wide-Field Compton Telescope (WCT) performing deep all-sky surveys in combination with a Laue Lens Concentrator (LLC) that enables simultaneously very deep observations of selected narrow-field targets, utilizing the WCT as its focal plane. A boom or two separated spacecraft flying in formation will maintain the gamma-ray optics and detector at the lens' focal distance.

3.1. Wide-field Comton telescope (WCT)

Over its lifetime, the proposed mission should produce all-sky surveys in the energy range of hard X/soft gamma rays, i.e. 100 keV to 10 MeV: mapping out in detail the extended distributions of galactic positron annihilation radiation, and of various long-lived cosmic radioactivities; surveying a very large sample of galactic and extragalactic compact sources by characterizing their non-thermal spectra, and study their variability on all timescales; constraining the origin of soft gamma-ray cosmic background radiation. Although the WCT is a small satellite mission (an order of magnitude smaller than an ACT type mission [1]), the multiplexing advantage produced by its very wide field of view makes possible to achieve narrow line sensitivities of better than 10^{-6} ph s^{-1} cm^{-2} over a mission lifetime of two years. Given that nuclear line sensitivities have only improved by a factor of ~10 since the 1970 s, this "modest" order-of-magnitude improvement in all-sky sensitivity provided by the Compton focal plane itself would enable major advances in our study of Galactic nuclear processes.

At present, several options for a WCT are studied: the Japanese *Compton All Sky telescope* (CAST) is based on the Si/CdTe Compton Telescope of the Soft Gamma-ray Detector (SGD) on board Astro-H (presently in phase A with a launch in 2013, see [4]). The SGD units combine a stack of ~30 layers of Si PAD detectors and 8 layers of CdTe PAD detectors with a thickness of 0.75 mm. The sides are also surrounded by CdTe pixel detectors. Abundant R&D on the Si/CdTe Compton Camera Concept have been conducted by the groups at ISAS and at SLAC [5–7]. Compton telescopes utilizing Si-strips to track the gamma-rays have been developed in Germany for the MEGA and GRIPS projects [see e.g. [8,3]]. In the US a number of Compton detector technologies have been developed for the Advanced Compton Telescope Vision Mission [1]. Included in these are the high-resolution germanium detectors developed and flown on the Nuclear Compton Telescope (NCT) balloon payload [9]. A Germanium Compton Telescope (GCT) would be based on these technologies.

Gamma-ray emission may be substantially polarized due to the non-thermal nature of the underlying emission processes. Through its capacity of measuring polarization the WCT will add a new powerful scientific dimension to the observations. Such measurements will allow the discrimination between the different plausible emission processes at work, and will constrain the geometry of the emission sites. A sensitive measurement of 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 gamma-ray bursts.

3.2. Laue lens concentrator (LLC)

Major advances in Laue Lens Optics are a natural match to the Compton camera technologies that are being developed in the US and Japan. The LLC is a broad-band gamma-ray lens based on the principle of Laue diffraction of gamma-ray photons in mosaic crystals [10]; it uses the WCT as focal plane detector. Simultaneously to the all-sky survey of the WCT, the LLC will observe a significant sample of SNIa in the light of the ^{56}Co decay line at

847 keV, a gamma-ray line of highest astrophysical relevance. A possible model LLC payload, made of 2500 Au and Cu crystal tiles of 1.5×1.5 cm^2 each, has a total effective area of $\sim$500 cm^2 in the energy band 800–900 keV. The focal length is 68 m, the crystal weight is of 41 kg only. Recent advancements in Laue Lens development are described in [11]. Combined with the excellent background rejection of the focal plane detector (WCT), the LLC achieves sensitivities better than 10^{-6} cm^{-2} s^{-1} for broadened (3%) 847 keV lines.

3.3. Status

DUAL is part of the presently ongoing strategic planning exercises in Japan, Europe and the US, it is envisioned as a joint mission between JAXA, NASA and European national space agencies.

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