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A fine-grained silicon detector for high-energy gamma-ray astrophysics (*)

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Summary. — We propose a silicon telescope to be placed in a satellite for the search of γ-ray sources in the energy range between 25 MeV and 100 GeV. The proposed experiment will have an area of 2500 cm^2, an energy resolution ranging from 7% to 8% and an angular resolution from 0.2 and 0.1 degrees between 1 GeV and 10 GeV. The telescope is based on the use of silicon strip detectors. Together with the energy measurement, a calorimeter of this type allows the determination of the particle type and its arrival direction, through the analysis of the spatial and energetic distribution of the electromagnetic shower produced. Detectors based on silicon technology have many advantages for space applications: no gas refilling system or high voltages, no need of photomultipliers (low consumption), short dead time, possibility of self-triggering. The GILDA project has been designed having in mind the weight limitation of 400 kg required by the Resource-01 satellite and it is carried out in the framework of the RIM (Russian Italian Mission) program. The launch is foreseen for the beginning of the next century.

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1. – Introduction

The GILDA telescope, carrying out a gamma-astronomy experiment, will be placed on a «Resource-0» type space satellite, that will cover a circular orbit, with height of about 700 km and declination 98°. Since the main goal of these satellites is the Earth surface monitoring for the program of the Russian State Committee of Nature, they have a permanent orbital orientation, so that the axis of the GILDA telescope, installed in the after-body satellite module, is pointed along the perpendicular to the velocity vector in the plane of the orbit. Limitations in size, conditioned by the satellite hermetic module volume (a cylinder 110 cm in diameter and 75 in heght), and the allowed mass for the telescope (~ 400 kg) have been the principal characteristics considered in designing the experiment project. The planned duration of the experiment is not less than 5 years.

The high-energy gamma-astronomy development, during the last twenty years, was practically fully determined by two successful long-term experiments onboard of space satellites, COS-B and EGRET [1]. The continuous emerging of new astrophysical and cosmological problems requires for future experiments the realization of telescopes with parameters significantly improved in comparison with the previous missions. From a traditional point of view, this is achieved by lengthening the linear device size L and, consequently, the mass of the telescope and satellite (growing as L^3). Such kinds of experiments are becoming rather expensive and approaching the limited value in cost, satellite mass and consuming resources.

As we will show, the silicon technique allows to obtain a much wider solid-angle aperture; in this way we can have more sensitivity with less area (see table I).

2. – Main scientific objectives

The primary goal of the GILDA mission is the research and identification of new astrophysical sources, but also known objects and transient phenomena will be studied. The energy range between 30 and 100 GeV is completely unexplored up to now; with the GILDA apparatus many goals within this range can be pursued.

– *Compact gamma-ray sources*

The high-energy emission spectrum of Crab, Vela and Geminga pulsars will be studied and provide data to check the validity of different theories for gamma-ray pulsar emission mechanisms [2]; also variations of the spectrum slope will be analyzed.

The wide aperture and optimal orientation of the telescope allow a permanent sky monitoring also of high-energy variable gamma-ray sources. Long-term observations of gamma-ray pulsars in binary systems are interesting: objects such as CYG X-3 and HER X-1 will be studied. The ultrahigh-energy gamma emission from both the sources was detected repeatedly in wide atmospheric showers by ground-based observatories [3]. Moreover, the existence (known from X-ray data) of a processional period of about 35 days for HER X-1 source requires further studies. This is hard to achieve with EGRET because each region of the sky is observed every half week, but could be done by GILDA, thanks to its orbit which covers at least once a day the whole sky sphere. Finally, the observations of CYG X-3 and HER X-1 for long time periods could shed light on the controversial matter about the existence of sporadic high-energy gamma-ray sources in such binary systems.

– *Active Galactic Nuclei*

So far, EGRET has detected more than 40 Active Galactic Nuclei emitting gamma-rays. The intensity of the brightest, 3C279, was comparable with that of the Crab pulsar. Time variations for one of these sources were detected [4], but these kinds of studies with EGRET are strongly restricted by its short interval of permanent observations for one sky region.

The GILDA experiment will bring a significative progress in the investigation of AGNs, will search for new sources and study their energy spectra. The duration of the experiment allows a detailed study of long-time gamma-ray emission fluctuations.

Since the Whipple Observatory [5] has detected gamma-rays in the TEV range only from one of the AGNs of the EGRET catalogue [6], this may be the evidence of a weakening of the extragalactic radiation in the range above 100 GeV, probably due to interactions of high-energy gamma-rays with the intergalactic infrared radiation [7, 8]. The future detection of sharp drops in AGN's spectra can be used as an indirect measurement of the intensity of the intergalactic infrared radiation; this component is hard to measure due to the contamination of the galactic emission. On the other hand, if the next-generation infrared experiment (SIRFT) measures the extragalactic infrared background, the observation of an absorption in the spectra can give information on the distance of the source and then give an independent estimate of the Hubble constant [9].

– *Galactic diffuse emission*

The diffuse gamma-emission from the Galaxy is strongly correlated with the matter distribution in the Milky Way, because of its origin from the interaction between cosmic rays and interstellar gas. The preliminary EGRET results showed some changes in the spectrum slope at 300 MeV, caused by the increased influence of nucleon-nucleon interactions. A detailed spectrum—also in the high-energy range—and a fine-grained sky map of this emission will clarify the existing ideas about the galactic matter distribution.

– *Extragalactic diffuse emission*

GILDA large exposition at high latitudes allows to collect a high statistics in the study of extragalactic diffuse gamma-ray emission. Accurate investigations with a good spatial resolution are required for a separation of this radiation from the stronger galactic emission; these studies will help to solve the problem of the extragalactic component origin.

Existing theoretical models consider the extragalactic component either as the product of a Early Age Universe evolution (requiring a fully isotropic distribution) or as the total combination of the emission fluxes from a large number of discrete extragalactic sources.

– *Search for dark matter and new particles*

A large amount of study has been devoted to the search of Weakly Interacting Massive Particles (WIMP), due to their great importance from the cosmological point of view, since these particles are possible candidates of Dark Matter. Being also the lightest supersymmetric particles, they have great importance even in particle physics. Spectral features like gamma-ray lines in the energy range above 10 GeV may be considered as the manifestation of their annihilation processes [10, 11]. The free parameters in the existing theories produce great uncertainties in predictions of the gamma flux intensity, depending on the WIMP's annihilation processes, but an energy resolution around 10% can be enough to reveal the gamma lines [12].

– *Gamma-ray bursts*

They are now the most interesting and mysterious objects in the sky. The theoretical models trying to understand them can be divided into two big classes: cosmological and galactic. The major difficulty for galactic models in the explanation of the complete isotropy of the bursts distribution, while for the cosmological ones is the very high value of energy that must be released at the source ($\sim 10^{51}$ ergs). All the experimental data collected up to now do not give the possibility to discriminate among these options.

Detection of the burst spectra extension can be the way to establish the distance scale, through the intergalactic absorption mechanism.

– *Solar gamma flares*

In 1991 two flares from the Sun ($E \simeq$ hundreds of MeV) were detected in the Gamma-1 experiment [13, 14]; some solar flares in the same range were detected by EGRET. These unexpected events emphasize the importance of an active monitoring of the Sun as a scientific objective of GILDA experiment.

3. – The GILDA telescope

The GILDA design is derived from a refined study of the Wizard [15] silicon calorimeter that has already successfully flown in balloon experiments. The configuration of GILDA has a height of 42 cm, an area of $50 \times 50\ \text{cm}^2$ and a total showering length of $11\, X_0$.

The stratigraphy of the instrument is shown in fig. 1, while a more complete description can be found in [16]. The first twenty planes form the converter zone, in which the silicon layers, made of $125\,\mu$m strips, are separated by tungsten plates of thickness $0.07\, X_0$. The structure of the basic $6 \times 6\ \text{cm}^2$ module is shown in fig. 2 (left).

The last ten planes $E_1 \ldots E_{10}$, constituting the absorber, are composed of 3.6 mm silicon strips and separated by layers of active scintillating lead fibers, $1\, X_0$ total thickness. Between the converter and the absorber, an aluminum plate of $0.2\, X_0$ is placed in order to reduce the back-scattering of particles from the bottom of the calorimeter. The structure of the scintillating fibers is shown in fig. 2 and is described in [16]. The configuration is completed with a plastic anticoincidence scintillator A_{c} (3 cm thick) around the converter zone, and with two fiber scintillators (without lead); one, E_{01}, after the first seven planes (after $0.49\, X_0$) and the other, E_{02}, after fourteen planes from the top of the detector. The introduction of the first one allows to obtain a threshold for γ detection of 25 MeV.

Two triggers are adopted, for the low- and high-energy regions, respectively:

– $\overline{A_{\mathrm{c}}} \cdot (E_{01} \cdot \mathrm{OR} \cdot E_{02})$, up to 1 GeV.

– For high energy, to avoid the same problems as EGRET, we do not use the anticoincidence scintillators; in fact, since at energies greater than 1 GeV the number

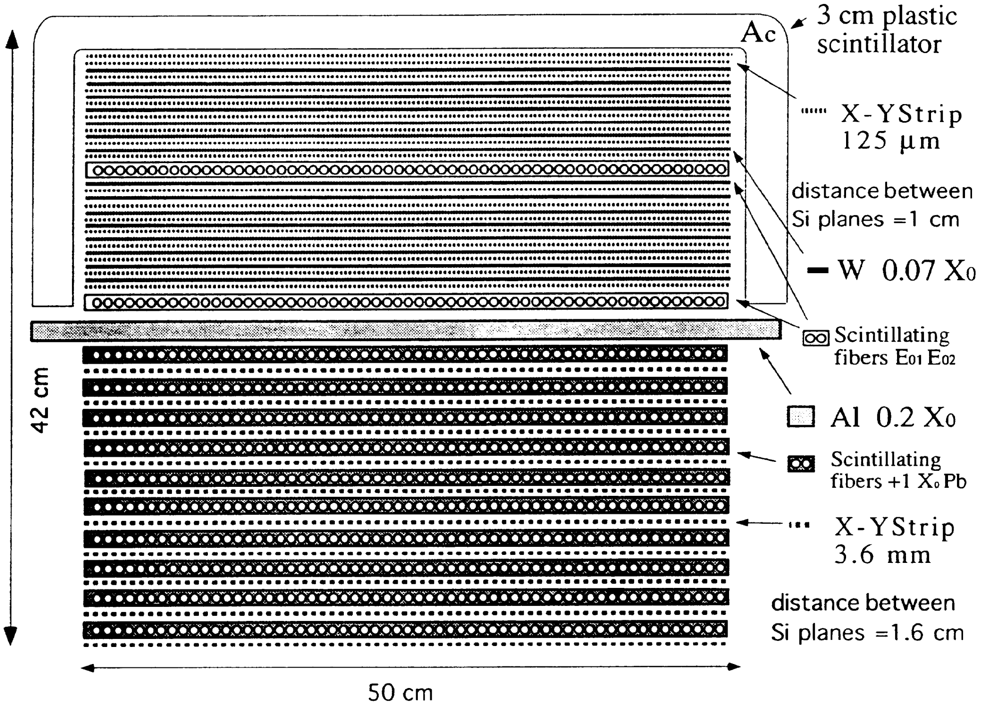

Fig. 1. – The stratigraphy of the GILDA detector.

of secondaries produced in a shower is relevant, the probability of having a back-scattered particle on the anticoincidence counters reaches the value of 70% for a 30 GeV gamma. Thus, the trigger is constituted by the OR between E_{01} and E_{02}, with the request of having at least *two* of the following conditions for the energy deposited in the first planes of the absorber:

$$E_2 > E_1\,,\qquad E_3 > E_2\,,\qquad E_4 > E_3\,,\qquad E_5 > E_4\,.$$

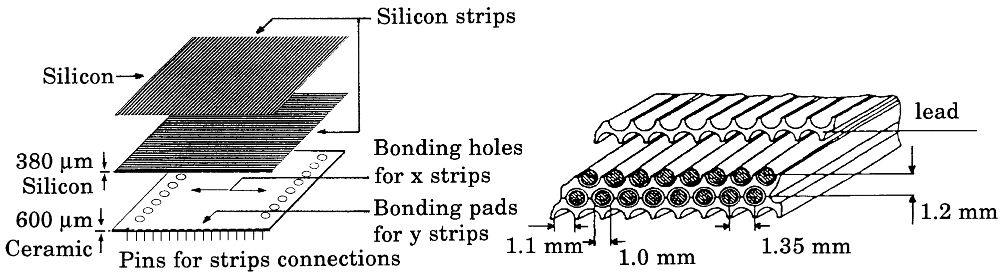

Fig. 2. – Structure of the basic 6×6 cm^2 silicon detector module (left), and of the lead scintillating fibers (right).

TABLE I. – *Some of the principal characteristics of* GILDA *telescope compared with those of* EGRET.

	EGRET	GILDA
Efficiency area (m^2)	0.16	0.14 (0.5 GeV)
(area × efficiency)	0.12	0.13 (1 GeV)
	0.07	0.17 (10 GeV)
Point-source sensitivity	$6 \cdot 10^{-8}$	$6 \cdot 10^{-8}$ (0.1 GeV)
(ph cm^{-2} s^{-1})	$1 \cdot 10^{-8}$	$9 \cdot 10^{-10}$ (1 GeV)
	$1 \cdot 10^{-9}$	$1 \cdot 10^{-10}$ (10 GeV)
Volume (m^3)	4.8	0.102
Mass (kg)	1830	400
Power (W)	190	250

This imposes a shower behavior for an entering particle. In this case, the elimination of particles inducing hadronic showers is realized on board with the aid of algorithms of pattern recognition.

4. – Results

In fig. 3, a comparison between GILDA and EGRET energy resolutions is presented. The total energy resolution of GILDA calorimeter is $\sim 6\%/\sqrt{E}\,(\mathrm{GeV})$ as far as the longitudinal leakage of the shower is negligible ($\leqslant 1$ GeV).

In the same figure we also show the energy resolution of another possible configuration obtained by substituting the $10\,X_0$ of lead scintillating fibers with the same radiation length amount of CsI(Tl) crystals, a possible alternative currently under study.

The results of our telescope angular resoluton are plotted in fig. 3 together with the EGRET ones.

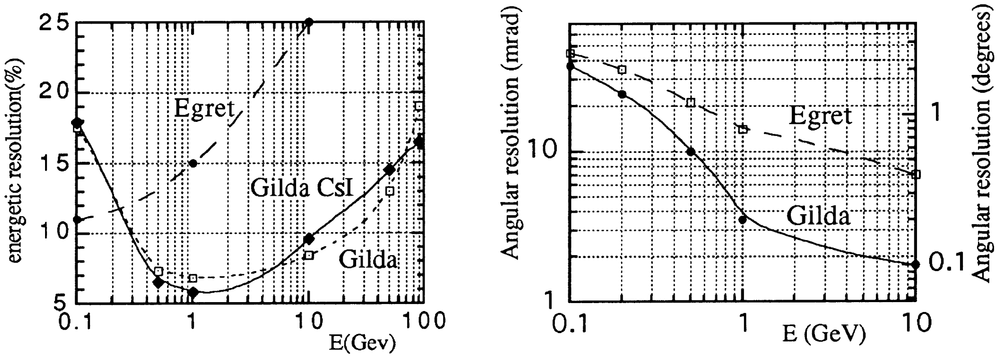

Fig. 3. – Simulated GILDA energy and angular resolution, compared with EGRET.

Finally, in table I we report some characteristics of the GILDA calorimeter, compared with EGRET.

5. – Conclusions

Our simulations have shown that the GILDA instrument is able to reach significantly better performances than the experiment EGRET on the CGRO, though having less area and weight, for the following reasons:

– the use of silicon strips instead of spark chambers as a main device for reconstructing the gamma trajectory;

– the elimination of the anticoincidence counters for the high-energy trigger, so that an efficiency of 70% up to 100 GeV can be reached;

– the elimination of TOF, with the consequent increase of the acceptance and decrease of the energetic detection threshold (25 MeV for GILDA and 35 for EGRET); again, the pattern recognition algorithms will substitute, off line, the TOF system, recognizing an upward going particle from a downward;

– the obtained compactness of the design which implies a very wide solid angle and so the possibility of monitoring many sources at the same time.

An important point is the modularity of our calorimeter that allows to easily change its lateral dimensions to tune the area, in an advanced project phase, to the maximum value permitted by the total weight of the payload. Of course, the collected statistics increases on widening the area.

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