Study of Early Universe Extreme Phenomena on Lomonosov Space Mission

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Study of Extreme Phenomena on the Lomonosov Satellite.

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Abstract.

The number of experiments on-board Lomonosov spacecraft are preparing now at SINP MSU in co-operation with other organisations. The main idea of Lomonosov mission is to study extreme astrophysical phenomena, such as cosmic gamma-ray bursts and ultra-high energy cosmic rays. These phenomena connect with a processes occurred in Early Universe in very distant astrophysical objects and give us information about first stages of Universe evolution. Thus, the Lomonosov mission scientific equipment includes several instruments for gamma-ray burst observation in optical, ultra-violet, X-rays and gamma-rays and the wide aperture telescope for ultra-high energy particle study by detection of ionisation light from its tracks in the Atmosphere. The main parameters and brief description of these instruments are presented.

KEYWORDS: cosmic gamma-ray bursts, ultra-high energy cosmic rays, space mission.

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1. Introduction

Study of extremely high energy and power process such as ultra-high energy cosmic rays (UHECR) and cosmic gamma-ray bursts (GRB) is of great importance not only for understanding of these phenomena, but also for physics of Early Universe.

Gamma-ray bursts are observed as short (from dozens of milliseconds up to dozens of seconds) increases of the gamma-quantum fluxes up to the energy of at least 10^9 eV. Discovered in 60s years of 20th century they are still at the cutting edge of astrophysics. These phenomena being the most powerful in the Universe occur not only in gamma-range, but also in optic and UV. The power of the explosion of these most bright astrophysical objects achieves 10^{51} - 10^{53} erg/s. GRB optical emission lasts up to several hours or even days, it can be an evidence of afterglow which appear after a giant explosion in the external shock wave expanding in the interstellar space and stellar wind of the exploded star. Probably, it is a process of collapse of a fast-rotating very massive star to a black hole in the case of so-called long-duration (more than a few seconds) bursts or merging of a neutron stars in tight binary system in the case of so-called short-duration (less than a second) bursts. However, these models are under discussion and the nature of this extraordinary phenomenon is still unknown. Due to GRB unusually powerful brightness, studying of their properties allows the researchers to look in the epoch of the early Universe, i.e. to study evolution of the stars and the stellar populations within the wide range of red shift from $z \sim 0.1$ up to $z \sim 15$ - 20, which is more than 98% of the age of our Universe.

The other extreme phenomena in the Universe are ultra-high energy cosmic rays, which most probable sources are the Active galactic nuclei (AGN). The fundamental problem is to estimate maximal particle energy, to which they could be accelerated in such sources, and whether there is a maximum energy to which particles can be accelerated in the Universe. Because AGN are very distant objects, UHECR go a long way before coming to the Earth. During their propagation UHECR lose energy due to photo-production of secondary particles (mostly pions) on the microwave background photons. This leads to a natural limit of observable cosmic ray particle energy and to the UHECR energy spectrum cut-off at the photo-production energy threshold, i.e. about $5 \cdot 10^{19}$ -10^{20} eV (effect of Greisen-Zatzepin-Kuz'min - cut-off). However, to the present we have only limited and contradictory information about the energy spectrum and composition of the cosmic particles at extremely high energies. Thus, it is not possible to make any final conclusions about the nature of UHECR, their sources location and mechanism of acceleration.

The mentioned above problems of study extreme phenomena dictate the scientific objectives of considerable space experiment and suggest a specific set of appropriate instruments.

2. Scientific objectives

The following problems should be studied during the Lomonosov mission:

- detection of GRBs in the optical and gamma ranges especially for study optical prompt emission and precursors.

- study of UHECR (10^{19} -10^{20} eV) near the GZK energy spectrum cut-off:

- study of the transient luminous phenomena in the upper atmosphere, started during the previous MSU space projects “Universitetsky – Tatiana” and “Universitetsky – Tatiana – 2″ (Garipov et al., 2005; Garipov et al., 2010).

- detection of the magnetosphere particles, which are the possible sources of transient and quasi-stationary phenomena in the upper atmosphere in the X-ray and optical ranges.

The main idea of GRB study in Lomonosov mission is to realize the simultaneous burst detection in gamma-rays and optical with possibility of prompt emission as well as precursor light curves being obtained. This gives unique information about GRB central engine functioning. On this way we plan to use the successive experience of ground-based system of wide field cameras and robotic telescopes MASTER, which had detected the prompt emission of several GRBs in September, 2010 (Gorbovskoy et al., 2011). The point is to use the co-aligned GRB gamma-ray monitor detectors and wide field optical cameras, which should operate continuously and store the data on trigger from GRB gamma-ray monitor. In this case the optical camera field of view (FOV) will be inside the gamma-ray detector FOV and there will not need to redirect the optical system (see Fig. 1). Thus, the time delay between optic and gamma-ray signals will be zero, and even the event pre-history including the possible precursors could be recorded. The other approach is based on the fast re-orientation technique with the use of MEMS technology or very fast (less than 1 s) rotating mirror. Source indication for optical system in this case is given by trigger from X-ray imager.

[Insert Fig. 1 here]

The other goal of Lomonosov mission is UHECR study. The Earth's atmosphere will be used as a "detector" of UHECR, which produce cascades of the secondary particles, i.e. extensive air (or Auger) showers (EAS), which can provide us information about the primary particle parameters. The bulk of secondary particles in EAS ionize the atoms of Atmosphere nitrogen and oxygen and lead to the so-called ionization glow, which is most intensive alone the EAS axis and looks like a track breaking out in a very short time (about several microseconds). The ionization light intensity gives the information about the energy of primary particle, while if we obtain the track image, it makes possible to estimate the arrival direction also. Thus, the instrument capable of UHECR ionization track image receiving is necessary.

Such instrument will be also able to detect so-called "transient luminous events" (TLE) in the upper Atmosphere. The nature of such TLEs is probably associated with atmospheric electricity phenomena. During the high-altitude electric discharges between the clouds in the upper atmosphere and the clouds and ionosphere (at the height of 10-70 km) there are observed short-time (duration from one up to hundreds of milliseconds) bursts of electromagnetic radiation within wide spectral range (from visual light up to UV and even X-rays and gamma-rays). Current experimental data about the discharges in the upper atmosphere have shown that the discharge phenomena in the upper atmosphere have global character, a number of the discharges and the energy released in these discharges are so high that we can expect certain relations between the discharge phenomena and other geophysical phenomena.

As the by-pass mission goal the study of charge particle fluxes in the near-Earth space and especially the high energy magnetosphere electrons could be considered. Radiation environment at low altitudes (less than ~ 500-600 km) is basically determined by the fluxes of quasi-trapped and precipitated particles of the Earth's radiation belts and the solar particles penetrating mainly into the polar caps regions. The scales of their time variations is very wide – from many years according to solar activity circularity down to so short as microseconds, probably, due to the processes of wave-particle interaction within the range of stable capture inside the geomagnetic trap. Experiments for the studies of these particles are needed to be conducted due to the timeliness of the following space-physics problem:

- what are the physical mechanisms which lead to the particles precipitation from the Earth's radiation belts and what is the main trigger for the beginning of intensification of this phenomenon under calm and disturbed geomagnetic and solar conditions. Besides extremely important fundamental physics which concerns the studies of these phenomena, magnetosphere particles penetrating into the atmosphere cause a number of interesting phenomena among which are local and wide-scale ionosphere disturbances, ozone layer variations and atmospheric ionization;
- is it possible that small-scale variations of penetrated particles (in first turn – relativistic electrons) are associated with TLE observed in the upper atmosphere;

- and at least, the altitude of the “Lomonosov” satellite’s orbit is close to that of the “basic” orbits of the manned space complexes, therefore complex studies of the radiation environment at this altitude is important from the point of radiation safety of space flights.

Scientific payload on board “Lomonosov” satellite will include a complex of instruments for the studies of the processes of the charged particles penetration into the upper atmosphere of the Earth and for the analysis of the radiation conditions at low altitudes.

3. Experimental technique and equipment

Scientific equipment installed on-board the Lomonosov satellite includes the number of instruments intended for solving scientific problems mentioned above:

- set of instruments for GRB study including gamma-ray monitor BDRG, optical wide-field cameras SHOCK and UFFO instrument consisting of UV and X-ray telescopes;

optical wide aperture telescope TUS for imaging of the UHECR tracks in the Atmosphere;

- set of instruments for study of energetic particle fluxes in the near-Earth space including magnetometer and high energy electron detector ELFIN and charge and neutral particle monitor DEPRON.

3.1. Gamma-ray monitor BDRG.

The device is intended for monitoring and locating of gamma-ray sources at the celestial vault within the gamma-range and for the production of the trigger signal for the ShOK wide-field optic cameras.

BDRG provides:

- monitoring of the transient astrophysical phenomena (GRBs, “X-ray novas”, “Soft gamma-ray repeaters”, etc.)
- timing of soft gamma-radiation of the X-ray double stars and pulsars.
- patrol of the solar radiation within the gamma-range.

BDRG instrument consists from three identical gamma-ray detector units BDRG-1…BDRG-3 with axes normally directed to each other. The system as a whole allows to observe a half of celestial sphere and to produce a rectangular coordinate system with the axes coinciding with the axes of the detectors. Each gamma-ray burst is detected by one of detectors or by a combination of two or three detectors. In the last case directing cosines which set the location of the source against the detecting system can be determined by the ratio of the counting rate amplitude increases in each detector to the total amplitude (the counting rate) which characterises the total flux falling on the detecting system. This method provides accuracy of the localisation of gamma-ray burst source on the sky for the most powerful events 1°-4° (Mazets and Golenetskii, 1981).

BDRG instrument main parameters are given in Table 1.

[Insert Table 1 here].

3.2 Space telescope TUS.

Orbital telescope TUS (Russian abbreviation for "Tracking Instrument") is intended for the observations of UV radiation (300-400 nm wavelength) bursts in the night atmosphere of the Earth.

TUS instrument includes a mirror-concentrator of about two meters diameter with a receiver of UV radiation – mosaic consists of 256 photomultiplyers – located in its center. Such space telescope will allow to detect UV radiation of the Auger showers from the particles, penetrating into the night atmosphere – in fact, very fast (microseconds' duration) tracks of the charged particles. A number of detected photons provides information for estimation of the primary particles' energy. Flux of these particles is very small (at energy of 10^{19} eV at the Earth it is about 1 particle per km^2 per year!) and possibility of their registration makes the space method a hands-down winner comparing with the ground-based instruments.

Parameters of the device are listed in Table 2.

[Insert Table 2 here]

The principles of observations with TUS are illustrated by Fig. 2.

[Insert Fig. 2 here]

3.3. UFFO instrument.

UFFO instrument consists from 20-cm UV-optic telescope SMT with fast rotating mirror and wide-field X-ray imager UBAT.

The main goal of the observations by means of the UV-telescope SMT is the recording of the intrinsic radiation of gamma-ray burst due to possibility of very fast (~1 s) rotation of the mirror focusing in the region of the burst localisation at the moment of the trigger of gamma-monitor or UBAT instrument which allows to obtain images within X-range (Chen et al., 2011). This instrument UBAT is based on combination of a coding mask and position-sensitive detector with pixels produced of LYSO scintillator. Specifications of UFFO instrument are listed in the Table 3.

[Insert Table 3 here]

The general view of UFFO instrument is given on Fig. 3.

[Insert Fig. 3 here]

3.4. Wide-field optical camera SHOK.

SHOK device consists of two stationary fast wide-angle cameras. Their field of view is situated within the area of gamma-bursts' detection of other instrumentation onboard "Lomonosov" satellite.

Each SHOK unit is an optic camera with a wide field of view, which must be within the field of view of the corresponding detector of the gamma-bursts monitor. Due to this feature it is possible to detect the burst within the optical and gamma-ray ranges simultaneously, and in the case of continuous observations a significant opportunity for measuring of optical curves of the gamma-ray burst prompt emission and their precursors' detection is provided.

Field of view of each camera is about 1000 square degrees, and maximum framing rate is about 5-7 frames/sec. In fact, cameras record “a movie” continuously, and in case of gamma-ray burst detection part of this movie can be transmitted to the Earth.

Among the bursts it is possible to process the images in order to find optical transients: supernovae, novae, “orphan” bursts, asteroids and near-space objects and space debris.

It must be emphasized that SHOK device will be the first orbital experiment with cameras of super-wide field. Development of detection methods of dangerous asteroids and space debris from space are of particular interest.

The photo of optical camera which is used in SHOK instrument is presented in Fig. 4.

[Insert Fig. 4 here]

3.5. DEPRON instrument.

DEPRON instrument (Dosimeter of Electrons, PROtons and Neutrons) is intended for the measurements of the absorbed doses and linear energy transfer spectra from high-energy electrons, protons and nuclei of space radiation, and for detecting of thermal and slow neutrons flux.

The instrument includes:

- Charged particles dosimeter based on semiconductor detector
- Thermal neutrons detector based on gas-discharge counter SI13N
- Circuits for analogue and digital processing of detectors' signals, for information storage and analysis
- Power supply units for the detectors and electronics

Charged particles detector is based on semiconductor one. For each detected particle an amplitude of impulse proportional to the energy lost by the particle in the detector's track sensitive volume is registered. The value of the absorbed radiation dose is determined by summation of all the values of energy losses in the detector's active zone and normalizing it by the mass of this zone.

Two semiconductor detectors each connected to its own channel of analogue signal processing are used for reliability. Besides, the detectors are disposed in sequence and operated with coincidence unit, which allows to use them as detector telescope. Registration of energy loss spectrum for the particles produced signals in both detectors allows to evaluate ionization losses spectrum for such particles.

Gas-discharge counter SI13N operated in a stable corona mode is used for thermal neutrons registration. Counter's operation is based on the following reaction between neutrons and He-3 filling the chamber: n+3He = p+T+764 keV.

Two counters SI13N are used for reliability by analogy with semiconductor unit. One counter is covered with moderator (organic glass) in order to widen sensitive zone into the slow neutrons area. Parameters of DEPRON instrument are given in the Table 4.

[Insert Table 4 here].

The ranges of the parameters, measured by means of SI13N counters – neutron flux density for the neutrons within energy ranges of 10^{-3} – 10^{2} eV is 0.1 – 10^{2} neutrons/(cm^2s).

3.6. ELFIN-L instrument.

ELFIN-L (Electron Loss and Fields Investigator for Lomonosov) instrument is a joint project of The Institute of Geophysics and Planetary Physics at the University of California Los Angeles (IGPP/UCLA) and Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University. It consist of a Flux Gate Magnetometer (FGM), an Energetic Particle Detector for Electrons (EPDE), and an Energetic Proton Detector for Ions (EPDI).

The main scientific objective of the MSU-UCLA collaboration will be to understand the dominant mechanisms of the loss of energetic electrons and ions. Energetic particles create a hazardous environment for satellites and humans in space and cause a number of satellite failures. Lomonosov, planned to launch in late 2011, is well-timed with respect to NASA’s upcoming Radiation Belt Storms Probe (RBSP) mission. The two RBSP as well as the three Time History of Events and Macro-scale Interactions During Substorms (THEMIS) spacecraft already on orbit will measure trapped radiation belt particles near the equator, which in conjunctions with Lomonosov will help understand the physical processes responsible for the dynamical evolution of the near-Earth radiation environment.

Parameters of the device and measured parameters are given in the Table 5.

[Insert Table 5 here]

3.7. The information unit (BI).

The Lomonosov on-board equipment also includes the information unit BI, which is needed in order to provide control of the scientific equipment complex onboard the “Lomonosov” satellite. It provides collection, storage and transmitting of the telemetric information to the Earth.

Information unit is developed in order to provide operation of the scientific equipment complex onboard the “Lomonosov” satellite and its operative and flexible control during the execution of the scientific program. The service systems of the basic satellite platform can’t fit the requirements of the unique scientific experiments – complicated scientific equipment, huge volume of scientific information storage, high-operative control of the equipment; therefore it was necessary to develop a special information unit.

Parameters of the unit are given in the Table 6.

[Insert Table 6 here].

4. Conclusion

The number of instruments installed on-board Lomonosov satellite provide the study of wide range of problems of modern astrophysics and space physics. The main ones are the study of extreme events in sources at cosmological distances such as UHECR and GRB. To be launched in nearest future Lomonosov mission gives the scientists a good opportunity to solve the above-mentioned problems.

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Caption to Figures

Fig. 1. Mutual position of fields of views of gamma detectors and optical cameras.

Fig. 2. Illustration of UHECR detection with TUS.

Fig. 3. UFFO instrument arrangement.

Fig.4. General view of the SHOK camera.

Table 1.

Parameters of BDRG instrument

Parameter, units	value
Energy range, MeV	0.01 – 3.0
Effective area (for three detectors), cm^2	~360
Time resolution, ms	1 (for the burst mode)
Mass (for one detector module), kg	5.5
Information capacity, MByte/day	~300
Field of view, sr	2π
Field of effective source locatiion. sr	$\pi/2$
Sensitivity to the burst detection, erg/cm^2	$\sim 10^{-7}$
Accuracy of burst source location	$\sim 1\text{-}4^{o}$ (for brightest events)
Expected number of detected bursts per year	~100
Power consumption, W	3.0 (1 detector block)

Table 2

Parameters of TUS instrument

Parameter, units	value
Area of the mirror, m^2	1.8
Focal distance, cm	150
Size of a cell, mm	15×15
Number of cells	256
Time step, mks	0.8
Energy threshold for UHECR, eV	$7 \cdot 10^{19}$
Observable area in the Atmosphere, km^2	6400
Track measurement step, km	5

Table 3.

Specifications of UBAT and SMT in UFFO instrument.

UBAT	Coded mask aperture camera	SMT	Ritchey-Chretien – MMA with rotator
Field of view, sr	~1.85 (90.2^{o}x90.2^{o})	Aperture, cm	10 (diameter)
Point spread function	≤10 arcmin in PSLC at 7σ	F-number	11.4
Energy range, keV	5 - 200	Field of view (FOV)	17'x17'
Number of pixels	48x48	Coverage of FOV	60^{o}x60^{o} (MMA) 90^{o}x90^{o} (RP)
Pixel size, mm^2	2.88x2.88x2	Detector	Intensified CCD
Effective area, cm^2	191.1	Detection element, pixels	256x256
Energy resolution, keV	2, FWHM at 60 keV	Pixel scale, arcsec	4
Quantum efficiency	99% at 100 keV	Location accuracy, arcsec	0.5
Sensitivity, mCrab	310 (10 s exposure at 5.5σ in 4050 keV)	Sensitivity	B=19.5 in white light in 100 s exposure at 5σ
Mass, kg	10	Wave length range, nm	200 - 650
Power consumption, W	10	Bright limit	mv = 6 mag
		Mass, kg	10.5
		Power consumption, W	10

Table 4.

Parameters of DEPRON instrument

Parameter, units	value
Absorbed dose, Gy	10^{-5} – 10
Absorbed dose rate, Gy/hour	10^{-6} – 10^{-1}
Flux density, particle/(cm^2s)	1 - 10^4
Mass (for one detector module), kg	3.0

Table 5.

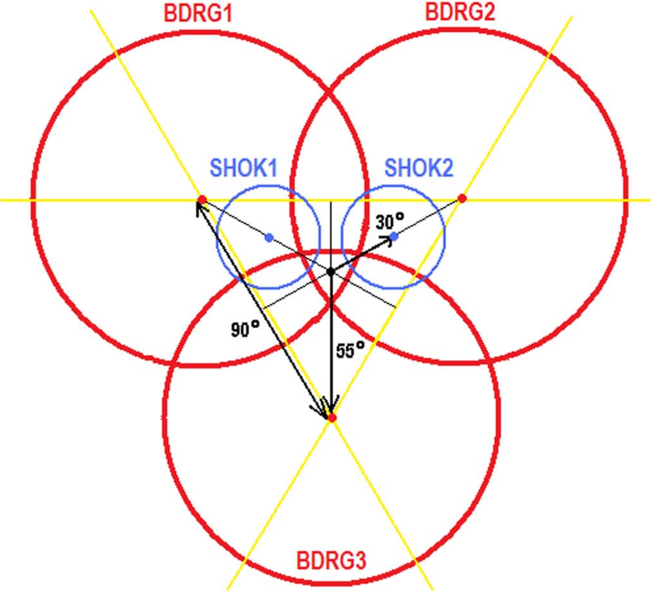
Parameters of ELFIN-L instrument

Parameter, units	value
Energy range for electrons, MeV	0.03 – 4.1
Field of view	37^ox37^o
Resolution of magnetometer, pTl	5
Sensitivity on 1 GHz, pTl	100

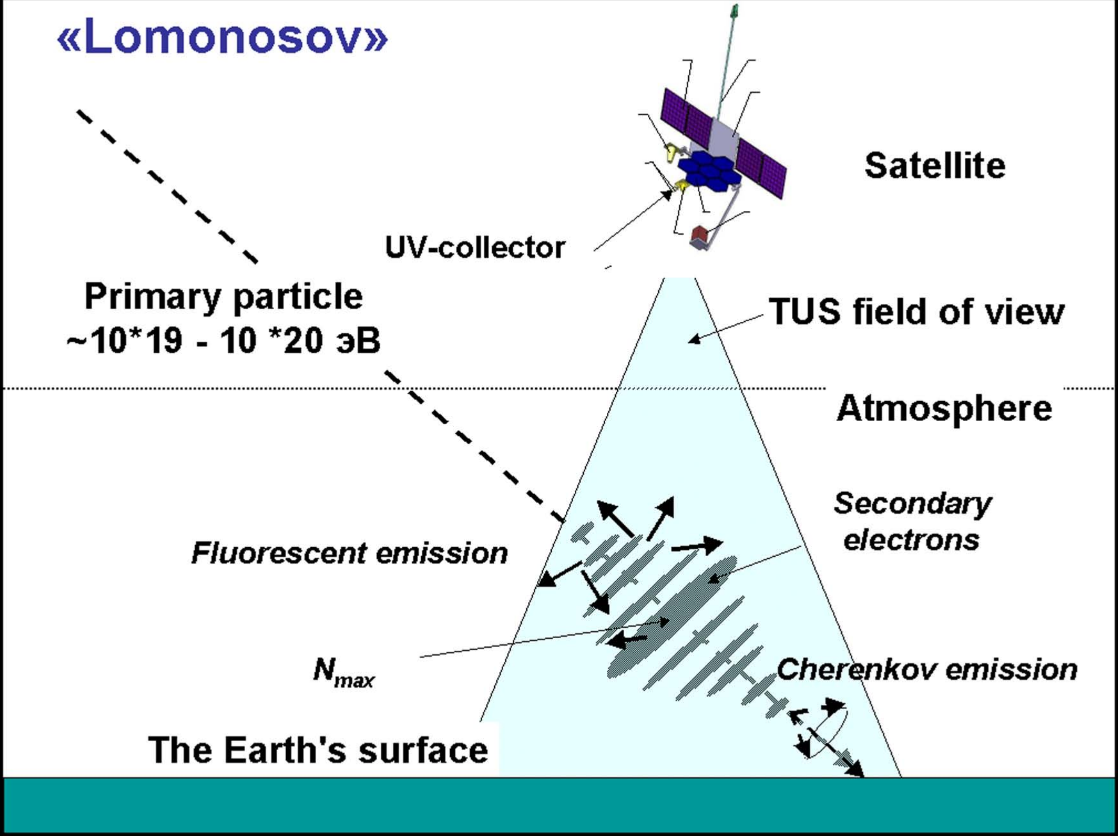
Table 6.

Parameters of BI instrument

Parameter, units	value
Data exchange rate, (interface Ethernet), Gbit/s	1
Data exchange rate, (interface CAN), Mbit/s	1
Command exchange rate, (interface CAN), Mbit/	1
Spacecraft command exchange rate, (interface MKO), Mbit/s	1
Data transmitting rate, (interface LVDS), Mbit/s	16
Scientific information memory volume (without bakup), TByte	1
Mass, kg	6
Power consumption, W	27


BDRG1
BDRG2
SHOK1
SHOK2
30°
90°
55°
BDRG3

«Lomonosov»



Satellite

UV-collector

Primary particle
~10*19 - 10 *20 эВ

TUS field of view

Atmosphere

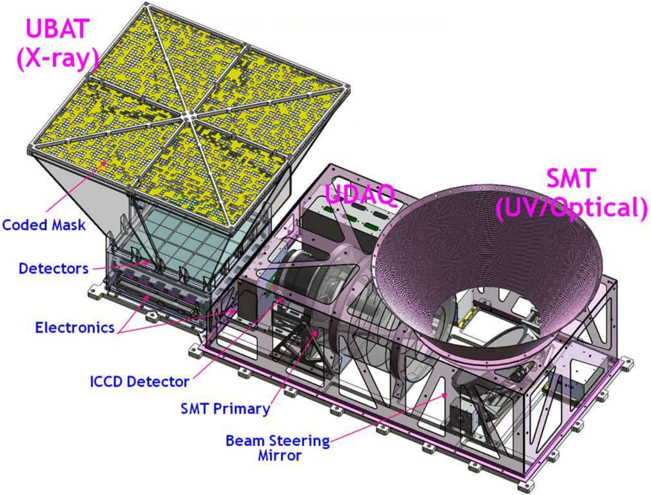
Secondary
electrons

Fluorescent emission

N_{max}

Cherenkov emission

The Earth's surface


UBAT
(X-ray)
UDAQ
SMT
(UV/Optical)
Coded Mask
Detectors
Electronics
ICCD Detector
SMT Primary
Beam Steering
Mirror


3
ALLIED
Vision Technologies
DHG-UV 52mm