# Light mirrors for VHE astronomy telescopes.

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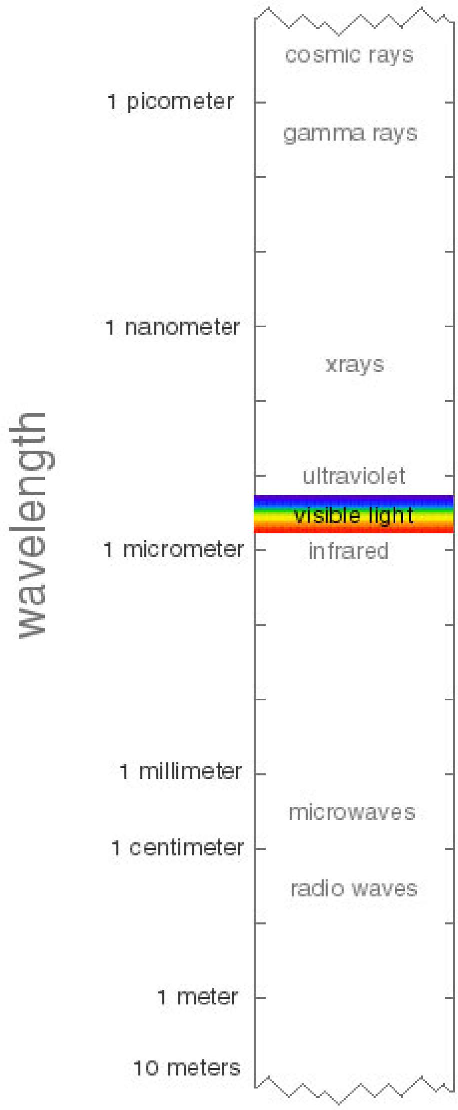
**Abstract.** The overview of light (weight) mirrors used in VHE astronomy telescopes is presented. The mirrors, which were developed in our laboratory, are described.

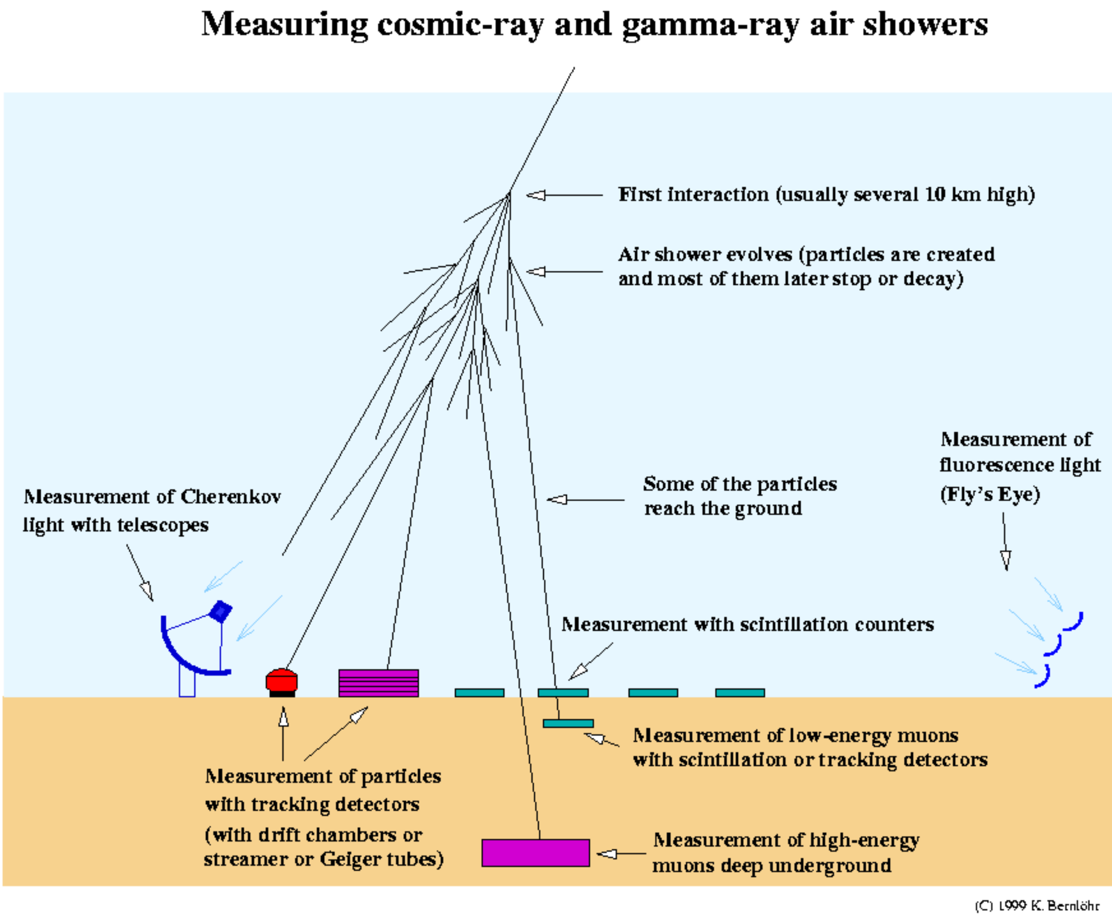
## New Astronomy.

" *We are beginning a new astronomy where the "light" is not electromagnetic radiation, such as radio waves, visible light, or gamma rays, but protons and nuclei* " : James Cronin ( Nobel laureate ).

The origin of the highest energy cosmic rays is still not known and is a burning question in high energy astrophysics research. The study of very high energy (VHE) particles may solve mysteries surrounding the Big Bang, black holes and sub-atomic particles.

Cosmic rays are fast-moving particles that constantly bombard the earth from all directions. Each second, about 200 cosmic particles of a few million electron volts strike every square meter of the earth but above the energy of $10^{20}$ eV, only one particle falls on a square kilometer in a century. To measure cosmic ray particles directly requires sending detectors to heights above the earth's atmosphere, using high-flying balloons and satellites. However, we can also detect cosmic rays indirectly on the surface of the earth by observing the showers of secondary particles that they produce in the air. The myriads of secondary

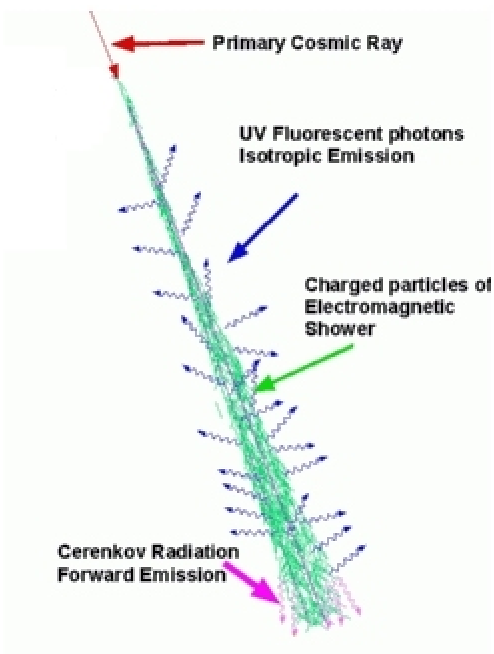





particles are registered with special detectors on the ground.

When a charged particle passes close to molecules in the atmosphere, it transfer some energy to the molecules and the molecules respond by emitting of UV fluorescence light as their electrons return to normal arrangement. Other effect is known as electromagnetic shock wave when a flash of Cerenkov light is generated by relativistic particles. The Cerenkov radiation is emitted only in the direction of particle shower whereas fluorescence is emitted in all directions.

Special telescopes can detect both light effects to study properties of primary cosmic particles.



## VHE astronomy telescopes.

VHE astronomy telescopes observe cosmic rays in much same way as a classical optical telescope might observe meteor trails. The difference is that the air shower flash is much fainter and much shorter. The telescope requires large collection aperture and a large main mirror for concentration of Cerenkov or fluorescence photons onto fast detector. The photomultiplier array in focal plane is generally used to detect this radiation in blue/UV light range. The telescopes typically consist one or more parabolic or spherical mirror between 2 and 17 meters in diameter. The mirrors with large diameters are usually constructed of multiple faces for easy of construction and weight reducing. Faint light signal call for optical system with small focal length/mirror diameter ratio ( $f_{no} \sim 1$ ).
The VHE telescopes require no significant spatial resolution comparable to optical telescopes. The resolution in tenths of degrees is tolerated.

### A segmentation scheme of large mirrors.

Requirement to see fainter objects leads to the desire for larger telescopes. But as the size of the telescope mirror gets bigger, the whole telescope is very expensive. Today's and future classical large telescope mirrors are built segmented similar to VHE telescopes. The cost of segmented mirror is significantly less than a single monster mirror. There are fundamentally two methods of segmenting a mirror: quadrangular segmentation or hexagonal segmentation. The identical regular hexagon is the polygon that can best cover a plane but hexagonal mirror segments are not identical. The segments have irregular shapes due to the curvature of whole mirror.

The hexagonal segments are often changed for circular shape by reasons of easy manufacturing and the cost but the hexagonal segments cover the telescope mirror more effective than circular segments. The hexagons and quadrangles fit together edge to edge and only little space is wasted between the segments. The array of circular segments has gaps where any incident light is reflected.

## The thickness and size of mirror segments.

**The thickness.**

The minimal thickness of mirrors is given by required thermal and gravity stability of reflective surface of mirrors. Of course the thick mirror keep the shape better than thin mirror and the minimal thickness depends on its structural material. The larger mirror calls for thicker substrate but the mirrors are manufactured as light as possible without apparent shape stability degradation.

The mirrors segments for VHE telescopes have usually thickness in range between **10 mm** and **25 mm.**

**The size.**

The telescope mirror should be segmented into relatively small mirror “tiles” to reduce the cost of the mirror. The inexpensive small segments are mounted into an array that works as one giant mirror and the cost of mechanical structure are taken into account. The support point structure is more complicated when the number of segment is increasing so the suitable lower limit of segment size exists. On the other hand there is an upper limit of the segment size. This limit is given by available technology of polishing, vacuum vaporization and so on without special requirements on building of new installations. That investment tends to become a significant part of the telescope cost. The cost of mirrors increases rapidly for sizes beyond **500 mm to 600 mm** ( 800 mm ) and these sizes are most often used in VHE telescopes.

## The optical quality of thin mirror segments.

Typical classical optical telescopes require high angular resolution in order tenths of arc second (a diffraction-limited case). The VHE telescopes call for resolution in tenths of degree only. The mirrors must have an optical quality such that the spot size is contained within the entrance aperture for each photo-multiplier of detector array. The surface quality of mirror segments is then determined by **slope error**, which is usually limited by $\delta \sim$ **1 mRad**. The main parameter of a mirror is radius of curvature. The allowed tolerance on nominal value is usually $\Delta$**R = 1 %.**

The mirror should be highly reflective for UV/blue region. The required **reflectivity** should be near value **90 %.**

## Materials of thin mirror segments.

The glass and ceramics are traditional materials for manufacturing of classical telescope mirror (monolithic or segmented) by reason of their thermal and weight stability. The relatively low requirements on optical quality of mirror segments for VHE telescopes leads to using of other material thin substrates.

The list of used materials in accordance with using.

## Glass

### - Low expansion borosilicate glass ( PYREX, TEMPAX, SIMAX )

The mirror substrate with good thermal properties is molded with approximate required radius of curvature. The milling, grinding and polishing lead to right radius of curvature. The front surface is aluminized and protected by a thin surface layer.

The mirrors have a good optical quality and shape stability.

### - FLOAT glass sheet

Float glass is soda-lime glass manufactured by floating on molten tin, commonly available as window glass for small thickness. By slumping float glass in an oven on a mold, smooth surface mirrors can be made which may require no polishing. The following operation is similar to above paragraph , the surface is aluminized and protected by thin layer.

This mirror has worse optical quality than previous mirrors.

## Aluminum.

Aluminum, either in bulk form or in the form of relatively thin aluminium plates strengthened by a honeycomb backing structure. Modern diamond micro-lathes allow to machine the aluminium to provide a reflective surface, without a special reflective coating.

Diamond milled aluminium mirrors have bad thermal stability and require a heating to keep optical parameters when surrounding temperature is variable.

## Composite material.

The material is a carbon fiber plastic. The mirrors are replicated using a mandrel. The mirrors are light, smooth, durable and have suitable optical quality but material is approximately four time the cost of glass. So they are not usually used excepting the Japan project named CANGAROO. The mirror substrate is composed from two thin carbon fiber substrates of 3 mm thick and 10mm polystyrene foam (a sandwich). The sandwich is covered with a resin coating and on it, aluminium sheet of 1 mm thick is attached. Final operation is coating by a protection thin layer.

The described mirrors have not comparable optical quality to the glass and aluminium mirrors but there is not too exacting optical criteria for VHE telescopes. The main problem is today's cost,

## The thin mirrors developed in Joint Laboratory of Optics of PU and Inst. of Physics AS CR.

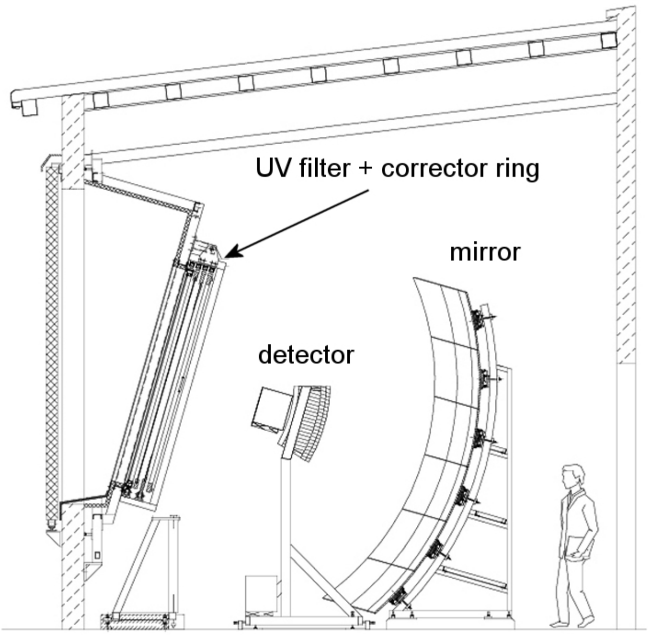
### History.

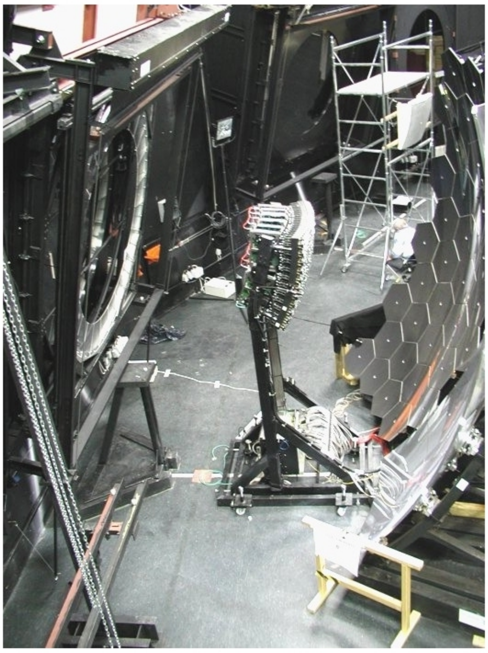
The first thin mirrors were developed in our laboratory for VHE project named CAT (Cerenkov Array Telescope) in French Pyrenees. The special glass

SIMAX was used as mirror substrate. This idea is know-how of our laboratory. The SIMAX is comparable to more expensive PYREX glass that is usually used for similar applications. The mirrors had the diameter 500 mm and the thickness 11 mm. We simulated the distortion of the mirror segment by gravity in wide range of temperatures using the finite element analysis. The distortion of this mirror is negligible. The reflecting surface was created by evaporating a thin aluminium layer and the reflective surface was protected by an additional layer of $SiO_2$. CAT telescope consists of 90 mirror segments and works already several years. Then we supplied similar mirrors for other project in French Pyrenees named CELESTE.

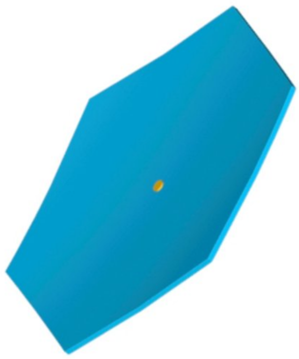
**Today.**

We are collaboration members of new VHE project named AUGER. The Pierre Auger observatory will be world's biggest cosmic ray detector. The part of the observatory will be fluorescence telescopes. The optical layout of telescope is modified version of Schmidt camera with approximately square mirror with dimension about 3600 mm x 3600 mm. Of course the mirror is segmented.

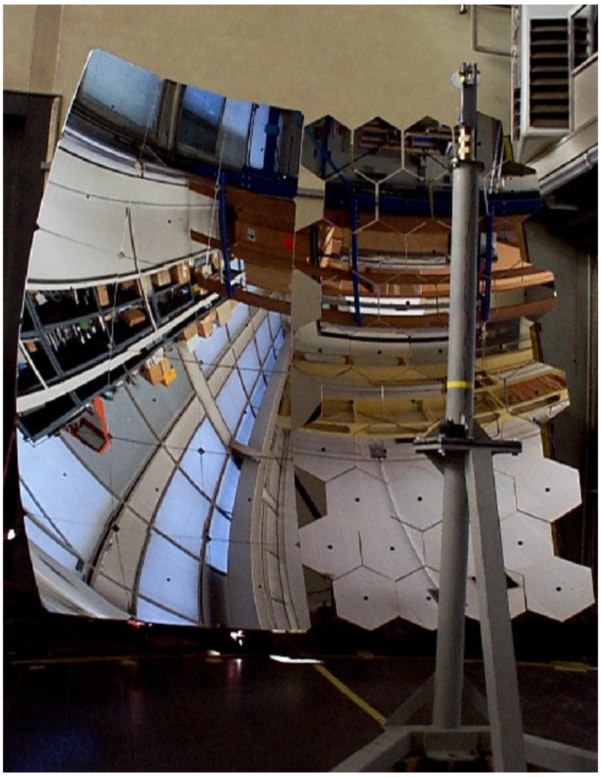


We changed our original circular mirrors with diameter of 500 mm into quasi-hexagonal shapes with the larger size at the same time. The hexagons cover the main mirror better than circles. The light losses are eliminated. Our new hexagonal type of mirrors has thickness 17 mm and circumscribed diameter over 600 mm.



**Note:**



The quasi- hexagon and the quadrangle segmentations of mirror are comparable each other. Both methods cover a spherical surface without significantly waste gaps. The hexagonal shape is close to circular and this shape facilitates milling, grinding and polishing of spherical surfaces. The quadrangle shape increases a difficulty of those operations. That is way the quadrangle shapes are used only in case when the described technology operations are not necessary. The first case is a slumped float mirror and the second case is a diamond turned aluminium mirror.

The good example is the prototype of the fluorescence telescope mirror for Auger project, which was competed from our quasi-hexagonal mirrors and from German quasi-square mirrors for comparison. Our mirrors are made from the Simax (glass) and German mirror are made from an aluminum (diamond turned).

**Conclusion.**

We present overview of thin mirrors used in VHE astronomy telescopes and we describe the mirrors developed in our laboratory.

**Acknowledgments :** We thank the Ministry of Education of the Czech Republic for its financial support under grants LN00A006, Ingo LA 134 and the Grand Agency of Academy of Sciences of the Czech Republic for project A1010928.

[1] CAT, http:// lpnp90.in2p3.fr/~cat
[2] CELESTE, http:// wwwcenbg.in2p3.fr/extra/Astroparticule/celeste/e-index.html
[3] Auger, http:// www.auger.org
[4] HESS , http:// www.mpi-hd.mpg.de/html/HESS/HESS.html
[5] VERITAS , http:// veritas.sao.arizona.edu/index.html
[6] CANGAROO III , http:// icrhp9.icrr.u-tokyo.ac.jp/c-iii.html
[7] MAGIC, http://hegra1.mppmu.mpg.de/MAGICWeb/
[8] TELESCOPE ARRAY, http://www-ta.icrr.u-tokyo.ac.jp