Observing the Crab Nebula Using LXeGRIT

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Scientific Motivation

Different types of objects in the Universe emit different types of radiation. Therefore, it is important to study the Universe with various kinds of space observatories. Gamma-ray astronomy is the astronomical observation of gamma rays. Observations in the gamma-ray range are appropriate to study nuclear and elementary particle astrophysics and astronomical objects under extreme conditions of gravitational and electromagnetic forces, and temperature with photon energies above 100 KeV. The most known cases are gamma rays from solar flares and Earth's atmosphere which are generated in the MeV range.

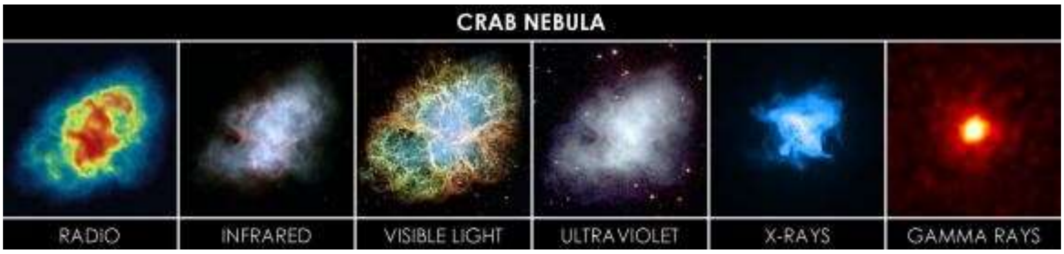
The mechanisms by which gamma rays are emitted are diverse. They demonstrate extreme events like supernovae explosions, and the behavior of matter in extreme conditions, such as pulsars and blazars. Electron-positron annihilation, the inverse Compton effect, the decay of radioactive materials in space, and interactions of energetic electrons with magnetic fields are some examples of these mechanisms. In the 1960s, scientists developed the ability to detect these emissions for the first time, and they have been looking at them ever since with different methods.

Gamma-ray astronomy developed when it was possible to get detectors above all or most of the atmosphere, using balloons or spacecraft. The reason why the detectors should be placed above the Earth's atmosphere is that gamma-rays coming from space are mostly absorbed by the Earth's atmosphere. In other words, signals from gamma rays below 1 TeV cannot be recorded on ground. Scientists can explore new physics, test theories, and conduct experiments that are not possible in Earth-bound laboratories by exploring the universe at high energies so gamma-ray astronomy offers unique opportunities.

One of the important candidates for studying the Universe in the gamma-ray range is the Crab nebula. Not only the Crab nebula tells us about a young pulsar but studying it can also answer questions about the fate and mass of its progenitor star, the mechanism that drives a supernova explosion, and cosmic-ray production. A complete understanding of its structure can lead to a better understanding of supernova remnants, gamma-ray pulsars, binary evolution, nucleosynthesis, and perhaps even the central engines in galaxies. The Crab nebula has been described by many scientists, however there is still no unique answer to a question about that; what exactly is the pulsar input into the nebula?

The Crab nebula is believed to be a supernova remnant. It is a pulsar wind nebula in the constellation of Taurus. The nebula lies in the Perseus arm of the Milky Way galaxy, at a distance of about 6,500 light-years (2 Kpc) from Earth. It has a diameter of 11 light-years (3.4 pc) and is expanding at a rate of about 1,500 kilometers per second. At the center of the nebula lies the Crab pulsar, a neutron star 28-30 kilometers across with a spin rate of 30.2 times per second, which emits pulses of radiation from gamma rays to radio waves. The Crab nebula was the first astrophysical object confirmed to emit gamma rays in the very-high-energy (VHE) band above 100 GeV in energy. In 2019 the Crab nebula was observed to emit gamma rays over 100 TeV, making it the first identified source beyond 100 TeV.

The Crab pulsar emits an outflowing relativistic wind that generates synchrotron radiation. As that radiation strikes the material in the surrounding nebula, it generates the powerful gamma-ray emissions.



The Crab nebula seen in radio, infrared, visible light, ultraviolet, X-rays, and gamma-rays [1]

Technical Justification

There are different methods and instruments to observe gamma-rays. The American satellite Explorer 11 carried the first gamma-ray telescope in 1961. In the 1960s, the Vela defense satellites, designed to detect gamma rays from secret nuclear tests. In the 1970s, Earth-orbiting observatories found a number of gamma-ray point sources, including a strong source called Geminga, which identifies as a nearby pulsar. The Compton Gamma-ray Observatory, launched in 1991, has mapped thousands of celestial gamma-ray sources. The Fermi Gamma-ray Space Telescope, launched in 2008, discovered pulsars that emit only gamma rays. However, I am going to focus on a specific type of telescope which uses liquid xenon; liquid xenon telescopes. Among the techniques proposed for gamma-ray imaging and spectroscopy of astrophysical sources, the Liquid Xenon Time Projection Chamber (LXe-TPC) is among the most promising.

1. Image Credit: Crab Nebula in multiwavelength.png by Torres997, Public domain, CC BY-SA 3.0, 8 March 2015

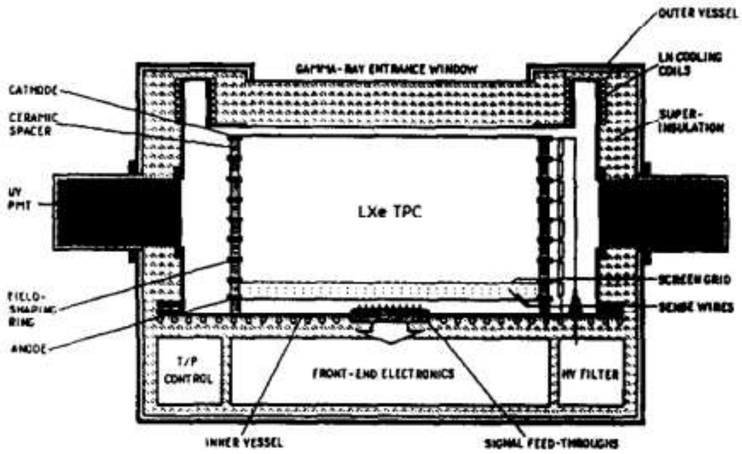
Gamma-ray telescopes with high imaging capability and flux sensitivity are essential for studying the highest-energy phenomena in the universe. High-quality imaging is needed to provide accurate positioning of the sources detected within the field of view. Good angular resolution is also needed to map regions of diffuse emission and separate point source contributions. Liquid Xenon Gamma-Ray Imaging Telescope (LXeGRIT) is a high-resolution telescope for imaging cosmic gamma-ray sources in the MeV region and it has an angular resolution better than 0.5°. The instrument consists of a 3-D Liquid Xenon Time Projection Chamber (LXe-TPC) as a gamma-ray detector and it is optimized for gamma rays in the range of 0.3-10 MeV.

The properties of liquid xenon like high density (3 g/cm^3) and high atomic number ($Z = 54$) have made it an ideal material for gamma-ray detection. This medium offers a combination of high detection efficiency, excellent spatial resolution and very good energy resolution. Gamma-rays in LXe lose their energy mostly via Compton scattering in energies above 250 KeV. The result of these interactions is ionization and excitation of xenon atoms and then a large number of electron-ion pairs (about 64,000 electrons per MeV) and a similar number of scintillation photons will be produced. Therefore, in the LXeGRIT TPC there are two kinds of particle; scintillation light and ionized electrons. Scintillation light is read using four UV sensitive photomultiplier tubes (PMTs) coupled to the interaction volume, while the ionization electrons are drifted via a uniform electric field through a pair of mutually orthogonal sets of parallel wire sense electrodes, and collected on an anode plane.

The LXe-TPC works based on the fact that free ionization electrons released by a charged particle in a liquid can move from their point of generation to a signal readout region under a uniform electric field. The collected charge signals on sensing electrodes are detected and provide both the spatial distribution of the ionizing event and its energy. For gamma rays, the electrons or positrons which are created by photoabsorption, Compton scattering, or pair production can excite the xenon atoms and as a result, a large number of electron-ion pairs and scintillation photons will produce.

The LXe-TPC can measure both the energy and the three-dimensional spatial position of every ionizing event occurring within its active volume. The scintillation light signal is fast (less than 5 ns) and thus provides an ideal marker of the time of origin of a gamma-ray interaction. On the other hand, by measuring the electron drift time, and based on the fact that the drift velocity is known, the Z-coordinate of the interaction point, along the drift direction, can be determined. The other two spatial coordinates are deduced from the charge signals induced on the sensor electrodes. And finally, the event energy is determined by the charge collected at the anode.

When the information about the spatial coordinates of all interaction points and the energy transferred to each Compton electron is determined, the arrival direction of the incident gamma-ray and its energy can be reconstructed. The arrival direction is confined to a cone of half opening angle equal to the scattering angle, and with its axis along the scattered gamma-ray direction. The location of the source is then found from the intersection of cones from a collection of individual events.

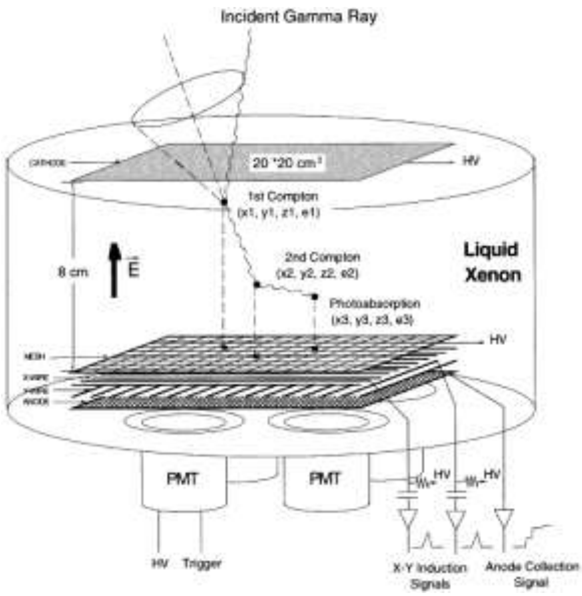


Schematic of the LXe-TPC detector [2]

Besides the determination of the energy and incident direction of a photon, designation of its polarization state can give further information on the source. One of the unique outcomes of the LXe-TPC imaging capability is its sensitivity as a Compton polarimeter. The main production mechanisms which can give polarized gamma-rays are: bremsstrahlung from electron beams, electron synchrotron radiation, electron curvature radiation, and gamma rays from the excitation of nuclei excited by directed ion beams. In the case of the Crab nebula, existence of VHE electrons in this source could yield polarized nebular gamma-rays of a few MeV. The answer can be determined by studying the Crab nebula using LXeGRIT.

The detector will be used as a balloon-borne payload for imaging MeV gamma-ray emission. Right now, it is sensitive to gamma rays from 300 KeV to 30 MeV so it can be used for studying the Crab nebula (as it was used previously). As mentioned it measures the energy and the 3-D location of each gamma-ray interaction with a resolution of 6% FWHM and 1 mm RMS at 1 MeV, within a 1 sr FOV. Its detection efficiency for Compton events is about 4% in the 1-3 MeV. Its 3 sigma continuum sensitivity of 1.8 multiplied by 10^{-7} ph $cm^{-2}s^{-1}KeV^{-1}$ for a nominal 10 hours' observation time, will allow to study a variety of sources with an imaging accuracy as good as 1 degree.

2. Image Credit: A Liquid Xenon Imaging Telescope for Gamma-Ray Astrophysics: Design and Expected Performance, E. Aprile et al.



Schematic view of the LXeTPC. Its operation as gamma-ray Compton telescope is illustrated [3]

The properties of the LXeGRIT can be found below;

Time Projection Chamber Characteristics	
LXe with < 1 ppb Purity	10 liters
Active Area	20 cm × 20 cm
Drift Gap	7 cm
Sensing Electrodes	62 X-wires, Y-wires, 4 Anodes
UV PMTs	4
Drift Velocity (1KV/cm)	2 mm/µm
Energy Resolution	5.9% FWHM (1 MeV)
Spatial Resolution	$\sigma_{x,y}$ = 1 mm, σ_z = 340 µm
Operating Temperature	-100 C
(dE/dx) mip	3.9 MeV/cm

Telescope Characteristics	
Angular Resolution	2^o RMS
Field of View	40^o
Energy Range	0.3 - 10 MeV
Active Shield (Side and Bottom)	5 cm NaI
Charged Particle Shield (Top)	1 cm Plastic Scintillator
Total Payload Weight	1910 lbs
Total Power	300 W

3. Image Credit: The electronics read out and data acquisition system for a liquid xenon time projection chamber as a balloon-borne Compton telescope, E. Aprile et al.

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