Results of a Study to Build a Gamma-Ray Telescope in an External Tank

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Abstract

In response to the ever-present need for a very large gamma-ray detector for energies greater than 100 MeV, a concept to build a telescope of 250,000 cm^2 sensitive area using a Space Shuttle External Tank (ET) is presented. In the Space Station era, for the first time, large detectors can be constructed on-orbit which would otherwise be limited in size by the launch vehicle. The ET will serve both as the spacecraft and the Cherenkov pressure vessel. The significant feature is that the sensitive area will be forty times that of the high energy detector on GRO and will be able to locate even the faintest sources from the GRO survey to a few arc minutes. The detection technique is based upon that originally proposed by Greisen.(1)

1. Introduction

The results to date in high energy gamma-ray astronomy are based primarily upon measurements with instruments of only about 600 cm^2 sensitive area. The next generation high energy detector, EGRET, on the Gamma Ray Observatory (GRO) will have a sensitive area of about an order of magnitude greater. The survey resulting from GRO, in particular from EGRET, should produce a list of sources with the same log N/log S distribution as in previous astronomical surveys. That is, the bulk of the sources should be at the limiting sensitivity of EGRET and due to the detection technique, be of maximum positional uncertainty. Spark chambers have been the workhorse in high energy gamma-ray astronomy since they provide simultaneously a large field of view and positional information which is needed to carry out the survey work. However, spark chambers become impractical if they are substantially larger than EGRET due to complexity and deadtime. In addition, when carrying out discrete source studies, the large field of view is of no advantage. Although GRO does not strain the limits of the Shuttle, a substantial increase in size (more than an order of magnitude) cannot be accommodated as a conventional payload. Therefore new directions must be sought to circumvent the launch capability within the current Shuttle system and a detection technique must be used which can easily be extended to very large areas without also multiplying the complexity.

2. Unconventional Solution

With the advent of the Space Station, unconventional approaches are possible for the construction of large cosmic-ray detectors. The gas-Cherenkov telescope originally conceived by Greisen and proven on several balloon flights(2,3,4) can provide the next advance in high energy gamma-ray detection. It is based upon the principle of imaging the Cherenkov light produced by the created electron pair. The gamma-ray imaging telescope system (GRITS) has 40 times the sensitive area of GRO, thus providing among other attendant improvements, measurements of variability one-fortieth as small. An angular resolution of a few arcminutes approaches the ultimate limit imposed by the physics of the pair-production mechanism. The key to this concept is the Space Station, and the availability on-orbit of the currently disposed of external tank (ET). The ET is ideal for this application since it is a large, clean, rigid, thin-walled, insulated, light-tight, gas-tight pressure vessel.

3. Gas Cherenkov Detection Technique

The combination of signatures and constraints utilized in this instrument result in a straightforward detection of gamma rays and inherently excellent non-gamma-ray background rejection. For the energies of concern, greater than 100 MeV, photons interact exclusively to produce an electron-positron pair. Figure 1 illustrates how the ET is to be instrumented. At the top of the telescope a thin converter is tightly sandwiched between two plastic scintillators to form the trigger module. The scintillator on the incident side is used as a veto to reject all singly-charged particles. The one on the exit side is used to detect the two charged particles resulting from the conversion of the neutral gamma ray.

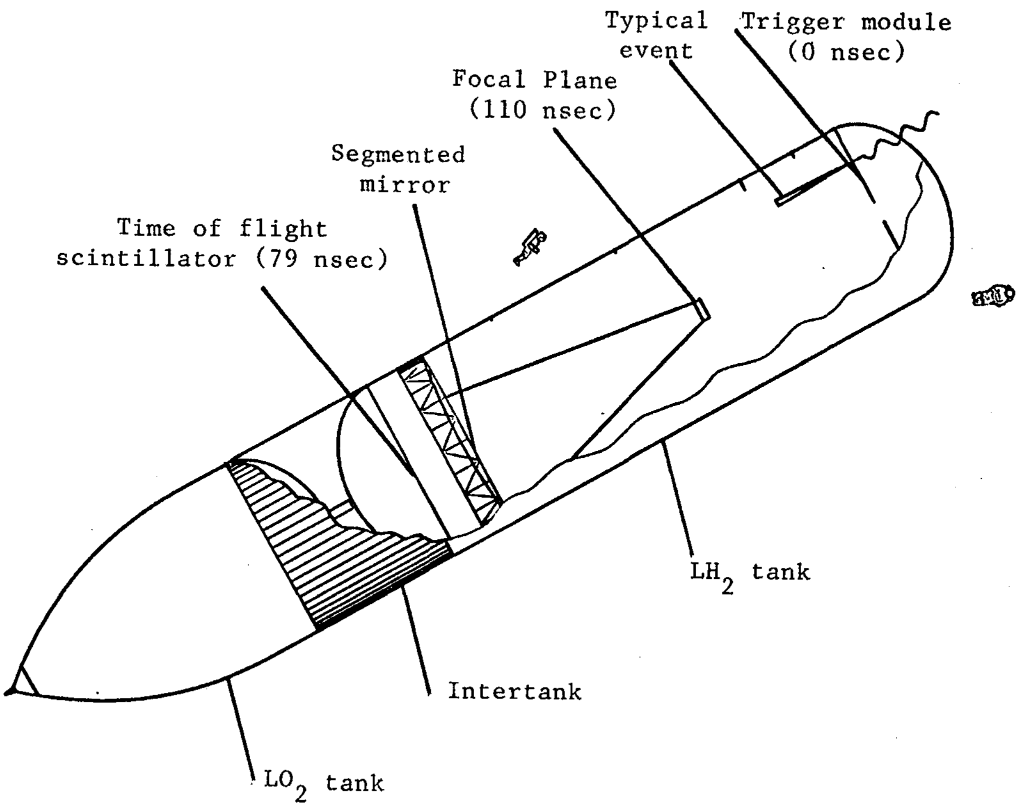

Figure 1. Major elements of the gamma-ray imaging telescope. The numbers indicate the elapsed time in nanoseconds for each signal composing the threefold time-delayed coincidence. In addition, there is a charged particle veto at t = 0. The overall length of the ET is 46.5 meters.

The energetic pair then travels the length of the telescope producing Cherenkov light in the gas-filled ET. For the index of refraction selected, 1.0000726 (air at 1/4 atm), the cone angle of emitted light is 1.4 deg, 5.8 visible light photons are produced per particle per meter of path length and the threshold for emission is at a Lorentz factor of 83. The two cones of light are imaged by a mirror at the far end of the ET onto an array of 127 photomultiplier tubes or a multineedle detector.(5) At the focus the two rings (not filled circles) of light arrive 110 nanosec after the pair creation. Data from the focal plane array are used to determine that the image and the amplitude of light corresponds to two rings of light. A time of flight (TOF) scintillator is placed behind the mirror to detect the passage of the charged pair 79 nanosec after the conversion of the gamma ray.

The electronic signature of an event is a threefold time-delayed coincidence of a pulse from the trigger module with no commensurate veto, 79 nanosec later a pulse in the TOF scintillator and 110 nanosec after the trigger, a pulse at the focal plane. During data reduction, the pulse height data from the light in the focal plane are not only used to validate the detection of two particles, but the location of the rings in the focal plane is used in the determination of the incident direction of the gamma ray. The combination of signatures and constraints make this detection technique naturally immune to all forms of non-gamma-ray background. Table 1 lists various types of background and the method the instrument uses to reject them.

For the converter material, active scintillators are used rather than a passive material such as lead. Measurement of the pulse height in the converter will determine the thickness of material through which the electron pair underwent multiple Coulomb scattering. Non-uniformimities in the light collecting efficiency which would otherwise make the pulse height measurements meaningless can be removed by making the same pulse height measurements in the thin trigger scintillator which will be of the same geometry and mounted directly under the converter scintillator. The amount of scattering in the trigger scintillator and the Cherenkov gas is both constant and smaller than that in the converter. Having determined the amount of scattering to expect in the converter will improve the uncertainties involved in determining the total amount of Coulomb scattering for each event. Knowing the scattering and having measured the angular separation of the particles in the focal plane will determine the energy of the incident gamma ray.

4. Angular Resolution and Sensitivity

Due to implementation constraints, only about half of the cross section of the ET can contain unobstructed trigger modules for a sensitive area of 250,000 cm^2. For converter thicknesses resulting in multiple Coulomb scattering commensurate with the emission angle, the sensitivity is roughly independent of the converter efficiency. To first order a resolution element is proportional to the square root of the converter thickness. Hence, a converter of 0.036 radiation lengths has been chosen to provide the optimum angular resolution with very little loss in sensitivity. This results in an RMS cell size of 1.1 degrees for energies greater than 300 MeV. (The emission angle at 300 MeV is 0.6 degrees.) Since the centroid uncertainty is about one-tenth of the cell size (and is roughly inversely proportional to energy), the error radius for all point sources seen with a signal to noise of ten is 7 arc minutes. Using only events of energy greater than 1 GeV with no loss in sensitivity gives a position to 2 arc minutes. The counting rates for various sources at energies greater than 300 MeV are:

R(Vela) = 70 counts/hour
R(Crab) = 9.8 counts/hour
R(Bkgd) = 0.8 counts/hour/cell (near the Crab and Vela).

Thus a signal to noise of 10 can be reached in 1.4 hours for Vela and in 11 hours for the Crab.

TABLE 1
Methods Of Rejection Of Non-Gamma-Ray Background

EFFECT	REJECTION METHOD
Singly charged primary	Amplitude and shape of light indicative of two rings and veto directly above converter with two-particle trigger directly below
Hadrons	Same as above and require Lorentz factor greater than 83
Chance coincidences	Amplitude and shape of light indicative of two rings and threefold time-delayed coincidence
Backward going events	Same as chance coincidences and not trigger veto
Decaying muons	Amplitude and shape of light indicative of two rings and Lorentz factor greater than 83
Off-axis events	Mirror and focal-plane geometry

References

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