SEARCH FOR PRIMARY COSMIC GAMMA RAYS WITH THE SATELLITE EXPLORER XI*

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The satellite Explorer XI (1961 ν), carrying an instrument designed to detect gamma rays of energy above about 50 Mev, was launched April 27, 1961. This is the latest effort in a program initiated in 1957 whose purpose was to search for gamma rays produced in interactions of cosmic rays with interstellar matter. Cline has published the results of his high-altitude balloon investigation of this problem.[1] Certain aspects of this and other problems of gamma-ray astronomy have been studied by other workers.[2-15]

The satellite instrument operated continuously and well until early September, 1961, when some deterioration connected with the power supply system became evident. Only about one fifth of the data acquired during this period has been analyzed, but since the results are of some astrophysical interest and because it will be several months before the remaining data are fully analyzed, we have decided to publish our preliminary findings.

The detector, shown in Fig. 1, functions as follows. Incident gamma rays are converted into electron-positron pairs in the sandwich crystal scintillator (alternate slabs of CsI and NaI) which is about one radiation length thick. The output of this scintillation detector is in time coincidence with the output of the Lucite Čerenkov counter which will respond if one or both members of the electron pair enter it. These two detectors serve to define the solid angle of the instrument which is about 0.25 steradian or 17° half-angle according to tests in a π^0-decay gamma-ray beam at the M.I.T. synchrotron. The plastic anticoincidence scintillator which surrounds the pair telescope prevents the detection of incident charged particles. When a coincidence between the signals from the telescope detectors occurs unaccompanied by a signal from the plastic anticoincidence detector, information concerning the pulse height from the sandwich crystal scintillator is telemetered.

During the period of the present analysis 127 events occurred which could be gamma rays. Analysis showed that 105 of these came from the general direction of the earth and are presumably, therefore, upward moving or albedo gamma rays produced in the earth's atmosphere by primary cosmic rays. The rate of these albedo gamma-ray events is in good agreement with the measurements made by Cline and both measurements are consistent with the gamma-ray measurements made with emulsions by Svensson.[16]

The strongest evidence that the remaining 22 events, which came from a variety of directions in space, are gamma rays is provided by the telemetered pulse-height distributions shown in Fig. 2. The upper curve shows a sample distribution obtained when the anticoincidence requirement was turned off. About 14% of the pulses are very large and so indicate large energy losses in the sandwich detector. These are presumably due to a combination of nuclear interactions of primary protons and incident charged cosmic rays having $Z > 1$. The lower distributions are for those events (with the anticoincidence re-

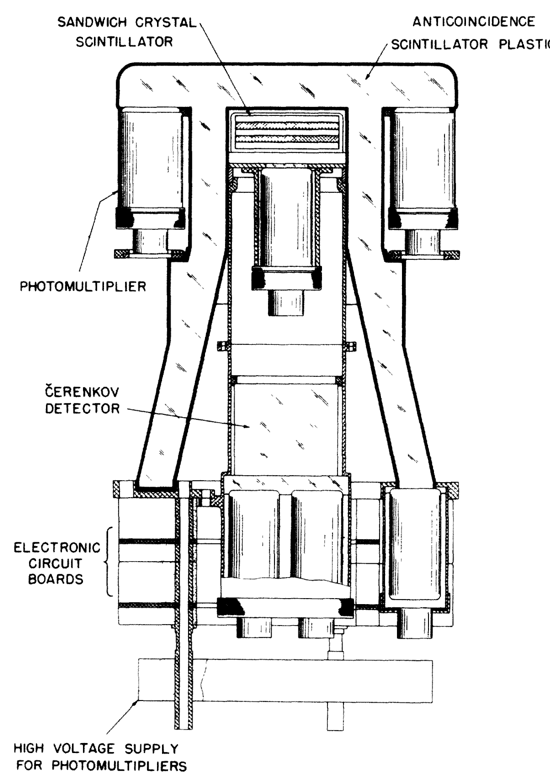

FIG. 1. Schematic view of the gamma-ray detector. The instrument is 20 inches high, 10 inches in diameter, weighs about 30 pounds, and operates on about 0.2 watt.

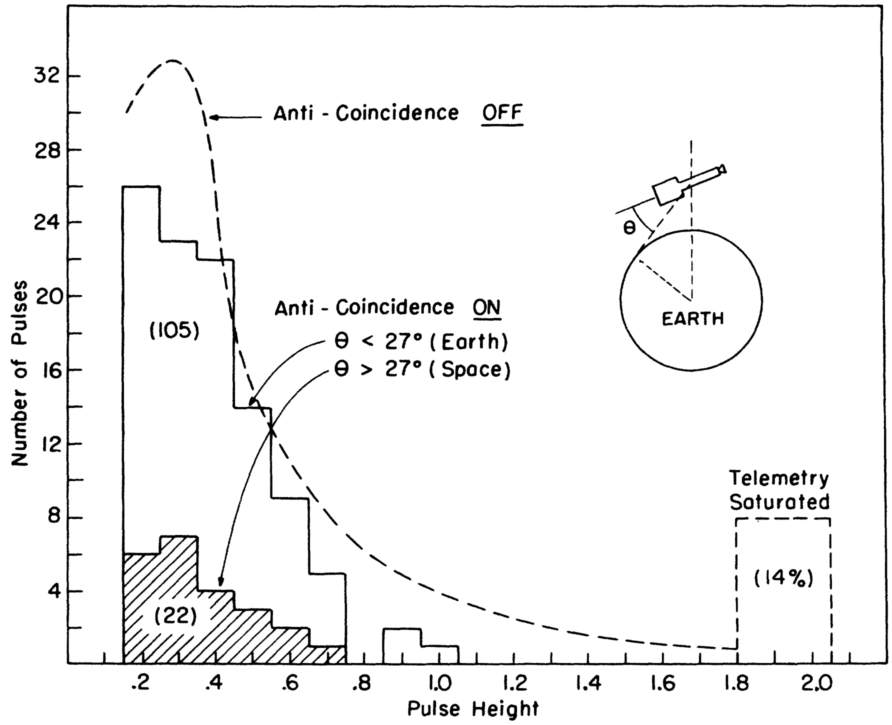

FIG. 2. Pulse-height distributions.

quirement turned on) which came from the directions of the earth and from space. The significant feature of these latter distributions is the lack of any very large energy losses. This lack is statistically significant for the group which came from the earth because 15 $(=0.14\times 105)$ large energy-loss events would be expected if this group were simply a small sample of the anticoincidence-off distribution. The measured distribution for this group is consistent with what is expected for gamma rays. Because there are too few events in the data shown in Fig. 2, a similar statement cannot be made about the distribution for the events which came from space. On the other hand, several hundred additional events, as yet unanalyzed for arrival directions, have been detected and their pulse-height distribution shows no evidence whatever of any large energy-loss events and is therefore similarly consistent with what is expected for gamma rays.

The above evidence plus laboratory experience with the instrument lend considerable support to our contention that gamma rays of nonterrestrial origin have been detected. Lacking, however, a pronounced anisotropy and direct absorber in—absorber out measurements, it remains barely possible that some or even all of the events we assigned to space arose from a subtle source of background. We cannot account for a background as large as would be implied and wish to emphasize that the a priori basis for the presence of a gamma-ray intensity of the general magnitude indicated by our measurements is very strong, as discussed later.

The analysis of the arrival direction data is complicated by the fact that all portions of the sky were not scanned for the same length of time. We have therefore divided the sky into a number of cells which are shown in Fig. 3. The upper number in each cell is the number of events detected while the lower number is the normalized scanning time. There is perhaps some tendency for the events to cluster about the galactic plane, particularly about the galactic center, but strong evidence for or against concentrations in these directions must await further data.

The average directional intensity of the events detected during the nine hours of observation is $J = 5.5\times 10^{-4}$ cm^{-2} sr^{-1} sec^{-1}. The efficiency of the instrument has been estimated to be 20%, and while this efficiency will eventually be known more accurately we now have confidence only that it lies in the range of 10 to 30%. Correspondingly the average directional intensity is uncertain but probably lies in the range (3.7-11) $\times 10^{-4}$ cm^{-2} sr^{-1} sec^{-1}.

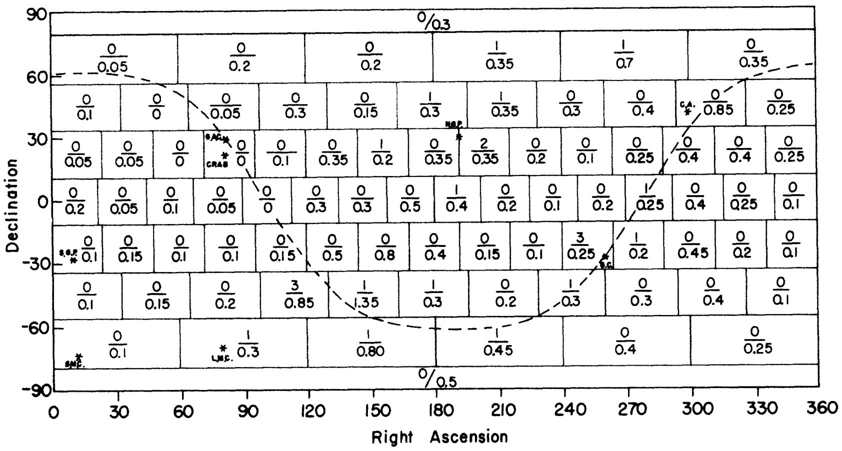

FIG. 3. Arrival direction data. In each cell the upper number is the number of gamma rays which arrived from within the cell, and the lower number is the normalized scanning time or number of events expected if the true distribution were isotropic. The dashed line is the plane of the galaxy. Also shown are the Galactic Anti-Center, Crab Nebula, South Galactic Pole, Small Magellanic Cloud, Large Magellanic Cloud, North Galactic Pole, Galactic Center, and Cygnus *A*.

The likely source of high-energy cosmic gamma rays is π^0-producing collisions between ordinary charged cosmic rays and gas. The source strength for the production of gamma rays by this process may be expressed as $S=jn\sigma m$, where j is the directional cosmic-ray intensity, n is the gas density in protons cm^{-3}, σ is the cosmic ray-proton cross section, and m is the average number of gamma rays produced per interaction. In the discussion which follows we have adopted the following numerical values: $j=0.3$ cm^{-2} sr^{-1} sec^{-1}, $\sigma=4\times10^{-26}$ cm^2, and $m=2$, respectively. These values have been chosen to take approximate account of interactions of the heavier nuclei as well as protons in the primary cosmic radiation.

1. Solar system. Suppose cosmic rays were confined to the solar system, say out to the orbit of Pluto. Then the average intensity of gamma rays would be $J=Sr$, where r is 6×10^{14} cm. To account for our observed J, the gas density would have to be 3×10^7 protons cm^{-3} or about 10^6 times greater than current estimates of this quality.

2. Galactic disk. Suppose, more reasonably, that cosmic rays are confined to the galactic disk, taken here to be 100 000 light years in diameter and 1000 light years thick and filled with a uniform gas of $n=1$ proton cm^{-3} The gamma-ray intensity averaged over all directions would be 7×10^{-5} cm^{-2} sr^{-1} sec^{-1}. Gamma rays from this source should arrive preferentially from the plane of the galaxy.

3. Galactic halo. If we take the halo to be a sphere of radius 30 000 light years filled with a gas of 10^{-2} proton cm^{-3} and take the earth to be 25 000 light years from the center, the average gamma-ray intensity from this source alone would be $\sim10^{-5}$ cm^{-2} sr^{-1} sec^{-1}. The directional intensity from the halo alone, under our assumptions, should be broadly peaked toward the galactic center.

4. Distant matter. Suppose, contrary to current thinking, that the cosmic-ray intensity throughout the universe is uniform and equal to its local value. If we assume that the gas density in intergalactic space is $\sim10^{-5}$ proton cm^{-3}, then the isotropic gamma-ray intensity would be

$$J=\alpha SR=1.6\times10^{-3}\ cm^{-2}\ sr^{-1}\ sec^{-1},$$

where $R=1.3\times10^{28}$ cm is the Hubble distance and $\alpha=0.4$ is a factor which corrects for the relativistic solid angle contraction of the receding distant matter. While this predicted intensity is a factor of 3 above our measured value, the experiment cannot rule out the seemingly unlikely possibility that substantially the same cosmic-ray intensity exists throughout the universe. Because the total mass of the universe in the form of interstellar gas is believed to be several orders of magnitude less than that in the form of intergalactic gas, the net contribution to the gamma-ray intensity from cosmic-ray collision processes in other galaxies is presumably small. Particular galaxies may well contribute measurable intensities.

The threshold energy for pair production by gamma rays which collide with optical photons is about 10^{12} ev and the density of starlight is such that gamma rays of this energy and greater should be only "local" in origin. Such gamma rays can generate detectable extensive air showers. Thus, a comparison between the directional distribution of gamma rays observed in the present experiment with that which may be determined in air shower experiments may decide the question of whether a significant production of gamma rays occurs in intergalactic space.

The experiment is capable of detecting gamma rays that arise from the decay of π^0 mesons produced in proton-antiproton annihilation, although the detection efficiency for these lower energy gamma rays, assuming annihilation essentially at rest, is probably not more than 10%. If we assume that our entire gamma-ray intensity arose from annihilation in the galactic disk and halo, the annihilation rate would have to be 2×10^{-25} cm^{-3} sec^{-1}. Since the lifetime against annihilation of an antiproton in the galactic halo or disk is short compared to the age of the galaxy, the above value is an upper bound to the antiproton production rate. We note that this rate is 1500 times less than the proton creation rate required by steady-state cosmology.

Listed in Table I are upper limits to the gamma-ray flux from a number of celestial objects. These upper limits are appropriate to a 95% statistical confidence level, and of course depend upon the estimated 20% detection efficiency.

Table I. Upper limits to gamma-ray flux, in cm^{-2} sec^{-1}.

Object	Upper limit
Cassiopeia *A*	1.2×10^{-2}
Andromeda	3.5×10^{-3}
Cygnus *A*	3.4×10^{-4}
Crab	3.7×10^{-2}
Galactic center	1.2×10^{-3}
Large Magellanic cloud	1.1×10^{-3}
Small Magellanic cloud	1.3×10^{-3}
Sun	1×10^{-2}

An experiment of this kind has of course relied upon the efforts and skills of many people. Particularly important have been the contributions of Dr. James Kupperian who coordinated the project and others of the Goddard Space Flight Center of NASA, personnel of the Marshall Space Flight Center of NASA who engineered and built much of the satellite, and G. Garmire, C. Moore, W. B. Smith, and E. Mangan of the M.I.T. Laboratory of Nuclear Science in which the gamma-ray detector was designed and built. A. Womack and A. Hershdorfer made essential contributions to the data analysis.

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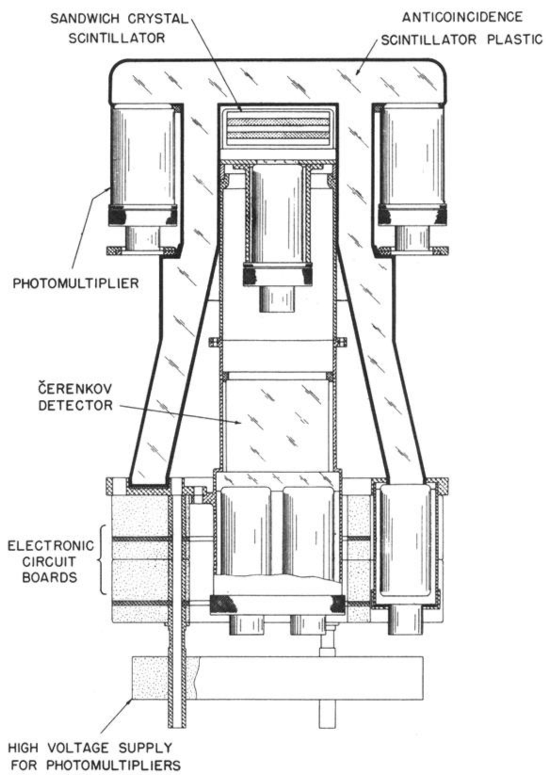

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