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ATMOSPHERIC GAMMA RADIATION

by

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ABSTRACT

During the summer of 1967, a series of balloon flights with a directional gamma-ray detector were made. The detector is collimated to a half-angle of about 12° and measurements are made over gamma-ray energies between 30-570 keV. The energy range is divided into 128 channels. Detailed knowledge of the instrument response allows the actual incident spectrum to be unfolded.

The altitude dependence of the gamma-ray count rate is well fit by curves of the form \( f = A \pm Be^{-p/D} \) where \( p \) is the pressure and the plus or minus sign is used for pressures below or above the maximum count rate altitude of about 75 mb. The spectra at different altitudes are presented.

The spectrum of the gamma radiation high in the atmosphere (3.5 mb) is analyzed in detail and appears to be proportional to the ionizing radiation which varies as a function of geomagnetic latitude. A small zenith angle dependence may have been observed. The \( \sim 500 \) keV feature which has been observed previously appears to be at 490
keV. The results of this experiment indicate that any contribution from a possible 511 keV annihilation energy line must be very small compared to the peak at 490 keV. Line features due to neutrons are present in the spectrum and appear to be of expected magnitude.

During one of the flights, the sun was in the field of view and an observed increase may be attributed to enhanced solar emission of gamma radiation. The increase appeared to remain constant for at least twenty minutes and the spectrum of the increase at the top of the atmosphere is fit by the curve $f(E) = 43.1 \, E^{-1.75 \pm 0.05}$ photons/cm$^2$-sec (where $E$ is in keV).
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I. INTRODUCTION

This thesis will concern the measurement of atmospheric gamma radiation in the energy range 30-570 keV between ground level and balloon altitudes of approximately 130,000 feet (corresponding to a depth of about 3.5 g/cm²). A basic division will be made between "ascent" (i.e., low altitude) data which is independent of celestial gamma radiation and balloon "float" data in which extraterrestrial gamma-ray effects are taken into consideration. "Float" data are those obtained at a few gm/cm² atmospheric depth.

Gamma-ray measurements have been made at ground level, and attempts have been made to explain the origin of the radiation by various authors (Hanson and Marker, 1964; Purvis and Foote, 1964). A comprehensive collection of papers on the subject of ground-level radiation is given by Adams and Lowder (1964). This paper will make no attempt to discuss the effects due to radiation from the ground.

Various authors have made measurements of gamma radiation in the atmosphere (Perlow and Kissinger, 1951; Jones, 1961; Anderson, 1961b; Charakhch'yan and Charakhch'yan, 1961; Peterson, 1963; Chupp, Sarkady, and Gilman, 1967; Chuykin, Romanov, and Lenin, 1967; Brini, Ciriegi, Fuligni, and Moretti, 1967). The experimental details of these papers are summarized in Table 1. Intercomparison of the results of these authors is difficult due to the fact that only observed count rates are reported. Because of varying geometries, efficiencies, and
<table>
<thead>
<tr>
<th>Author</th>
<th>Method</th>
<th>Energy Range</th>
<th>Altitude</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perlow and Kissinger, 1951</td>
<td>Rocket</td>
<td>.1-15 MeV</td>
<td>0-850 g/cm²</td>
<td>Geiger tubes</td>
</tr>
<tr>
<td>Jones, 1961</td>
<td>Balloon</td>
<td>.25-10 MeV</td>
<td>5-1000</td>
<td>CsI Phoswich</td>
</tr>
<tr>
<td>Anderson, 1961b</td>
<td>Balloon</td>
<td>30-300 keV</td>
<td>6-600</td>
<td>NaI Scintillator</td>
</tr>
<tr>
<td>Charakhch'yan and</td>
<td>Balloon</td>
<td>&gt;50 keV</td>
<td>6-1000</td>
<td>NaI Scintillator</td>
</tr>
<tr>
<td>Charakhch'yan, 1961</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peterson, 1963</td>
<td>Balloon</td>
<td>.4-3.4 MeV</td>
<td>6</td>
<td>NaI Phoswich</td>
</tr>
<tr>
<td>Chuykin, Romanov, and Lenin, 1967</td>
<td>Balloon</td>
<td>&gt;100 MeV</td>
<td>8-700</td>
<td>CsI Cerenkov</td>
</tr>
<tr>
<td>Brini, Ciriegi, Fuligni, and</td>
<td>Balloon</td>
<td>20-200 keV</td>
<td>10-1000</td>
<td>NaI Scintillator</td>
</tr>
<tr>
<td>Moretti, 1967</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chupp, Sarkady, and</td>
<td>Balloon</td>
<td>100-900 keV</td>
<td>4</td>
<td>CsI Phoswich</td>
</tr>
<tr>
<td>Gilman, 1967</td>
<td></td>
<td></td>
<td></td>
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</tbody>
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energy intervals, it is difficult to interpret their results in absolute flux units.

Due to the large number of balloon-borne experiments within the recent past, the gamma-ray background encountered at these altitudes has become of interest. One of the purposes of this paper is to summarize the measurement of this radiation so that the spectrum in absolute units may be determined at any altitude.

The production mechanisms thought to be responsible for the atmospheric gamma radiation (bremsstrahlung of electrons, electron-photon cascade, etc.) have not previously been shown to produce the observed spectrum. In the conclusion of this thesis the major production mechanisms will be described.

The existence of a high energy x-ray and gamma-ray diffuse interstellar flux due primarily to $\pi^0$ meson decay, bremsstrahlung, and Compton scattering has been postulated in various papers which are summarized by Fazio (1967). Measurements of such an isotropic flux up to 4.3 MeV have been made by Metzger, Anderson, Van Dilla, and Arnold (1964) on the spacecraft Ranger 5. Discrete x-ray sources were discovered in 1962 by Giacconi, Gursky, Paolini, and Rossi (1962). These discrete sources are thought to be due to either thermal emission or synchrotron radiation (Tucker, 1967). Celestial radiation must be added to production in the atmosphere at small depths where it is little attenuated.

The second part of this paper will be concerned with the radiation measured at balloon float altitudes (approximately $3.5 \text{ g/cm}^2$). A good understanding of the gamma-ray
production would be an asset to future balloon studies. At present, most directional balloon-borne detectors have been required to expend good viewing time in background measuring modes. If background intensities could be predicted with sufficient accuracy, perhaps the necessary time viewing background could be reduced.

The relative intensity of the gamma radiation generated in the atmosphere and the radiation due to the celestial background at float altitudes in question. Jacobson (1968), concludes that at 3.2 g/cm$^2$ the two components are approximately equal in the energy range 20-50 keV. Bleeker, Burger, Deerenberg, Scheepmaker, Swanenburg, Tanaka, Hayakawa, Makino, and Ogawa (1968) conclude that the celestial component is responsible for at least one-half of all of the radiation observed above 5 g/cm$^2$ for energies between 20-106 keV.

The results of our measurements at float altitudes allow us to examine the general form and outstanding features of the spectrum. The results may be compared with the measurements of other authors (Jacobson, 1968; Peterson, 1963; Chupp, Sarkady, and Gilman, 1967). Variations in the count rate can be evaluated in order to determine if they are due to changes in zenith angle and geomagnetic latitude.

Temporal changes in background counting rate have been observed (Haymes, Ellis, Fishman, Kurfess, and Tucker, 1968). This thesis will attempt to analyze such a variation in detail in an attempt to correlate the increase to solar activity of the type observed by deJager
(1967); Hudson, Peterson, and Schwartz (1968); and Cline and Holt (1968).

A tabulation of gamma radiation fluxes at various altitudes in the atmosphere will be presented in both graphic and equation form. In addition, an attempt will be made to correlate changes in these fluxes with geomagnetic latitude, zenith angle, atmospheric depth, and solar activity. An analysis of the spectrum will be made to identify the source of apparent line features.
II. APPARATUS

The gamma ray detection system used in the experiments described has been well described in several publications. The general purpose and basic design of the detector, pointing systems, and telemetry and recording systems are described in detail in Craddock (1967). The special configuration and details peculiar to each individual flight are detailed for the Crab Nebula flight by Ellis (1968), the flight that searched for hard radiation from the Virgo region by Fishman (1968), and the Cygnus region flight by Haymes, Ellis, Fishman, Glenn and Kurfess (1968).

Rather than attempt to go into a detailed description of each flight, the fundamentals of the system will be described and then the different features of each flight will be analyzed. A detailed description of the procedure necessary to convert count rates to isotropic flux will be given.

The detector common to all flights is a 2-inch thick sodium iodide (thallium activated) crystal which has a sensitive area of 75 cm$^2$. The incident gamma rays were collimated by an outer crystal arranged as shown in Figure 1.

To avoid counting events other than gamma rays entering the front of the telescope, pulses from the large crystal and $\frac{1}{8}$" plastic scintillator are in anti-coincidence with the pulses from the central crystal. In addition to rejecting charged particles, this arrangement reduces the contribution of Compton scattered photons which are not
FIGURE 1
totally absorbed in the guard crystal.

The output of the central phototube is fed into a 128-channel pulse-height analyzer. The pulse-height information is transmitted to a receiving station as a seven-bit digital word.

The NaI(Tl) gamma ray detector was designed to detect and measure the spectrum of radiation from discrete sources. It is well collimated to an opening angle of approximately 12° half-angle (0.135 steradians) and has a good resolution and high efficiency over the energy range from 30 to 580 keV. Figure 2 gives the percent absorption as a function of energy.

Before each flight, numerous energy calibrations were made by using gamma ray sources with known energy levels. To insure a constant calibration, the pulse-height measuring electronics and the central crystal were pressurized and maintained at a constant temperature. Pre-flight and post-flight energy calibrations were made to verify a constant energy to channel number correspondence.

In addition to the NaI(Tl) detector, an ion chamber of the type described by Neher (1953) and Neher and Johnston (1956) was flown. The ion chamber was sensitive to photons greater than 30 keV and to protons greater than 10 MeV. Further response data are given in Anderson, Despain, and Neher (1967). The time between pulses was telemetered to the ground station.

An eight-channel FM/FM telemetry system was used to transmit the scientific and engineering data to the ground station. In addition to the pulse-height data
ENERGY DEPENDENCE OF DETECTION EFFICIENCY

FIGURE 2
word, voltages monitoring the torque motor current, the right ascension drive frequency, a magnetometer, the reject rate, and the ion chamber were telemetered on individual subcarriers. Two commutators with twenty positions apiece also modulated individual subcarriers. Parameters monitored by the commutators include magnetometer output, temperatures, regulated voltages, torque motor current, pressures, and drive frequencies.

The ground station equipment was a set of subcarrier discriminators fed by a UHF radio receiver. A multi-track magnetic tape recorder recorded the output of the receiver, the discriminated pulse-height signal, the discriminated ion chamber signal, and a WWV time signal.

Various strip chart recorders and meters monitored the engineering data subcarriers to give a continuous real time display of the status of the gondola. Knowledge of the important regulating voltages, battery voltages, temperatures, pressures, and altitude enabled decisions to be made which minimized the chance of failure. A tonal command system allowed transmission of necessary commands to compensate for longitude drift and to replace any failing components with standby equipment.

The three flights in the summer of 1967 were made with two physically different crystal assemblies. These assemblies were specially built by the Harshaw Chemical Company. The first one (hereafter referred to as Detector A) was used for the Crab Nebula flight of June 4, 1967. The other detector assembly (referred to as Detector B) was used on both the Virgo flight on August 10, 1967, and
the Cygnus flight on August 29, 1967. The primary difference between detectors was that Detector B had undergone a modification of the original design and this modification reduced the absorbing material in front of the central crystal face, resulting in an improved effective efficiency. Figure 3 is a comparison of the flux attenuation factor as a function of energy for the two detectors. The flux attenuation factor is the reciprocal of the fraction of incident photons which are detected after passing through the photomultiplier tube, the guard plastic, and fabrication material. Figure 4 gives the full width-half maximum (FWHM) resolution of the two detectors, and Figure 5 gives the energy to channel number calibration for the three flights. A summary of the three flights is given in Table 2.

### TABLE 2

<table>
<thead>
<tr>
<th>Flight</th>
<th>Date</th>
<th>Detector</th>
<th>Energy Range</th>
<th>E/C*</th>
<th>Resolution @60</th>
<th>Resolution @661</th>
</tr>
</thead>
<tbody>
<tr>
<td>1967-1</td>
<td>4 Jun 67</td>
<td>A</td>
<td>30-570 keV</td>
<td>4.25</td>
<td>21%</td>
<td>9%</td>
</tr>
<tr>
<td>1967-2</td>
<td>10 Aug 67</td>
<td>B</td>
<td>27-560 keV</td>
<td>4.20</td>
<td>28%</td>
<td>13%</td>
</tr>
<tr>
<td>1967-3</td>
<td>29 Aug 67</td>
<td>B</td>
<td>32-564 keV</td>
<td>4.20</td>
<td>28%</td>
<td>13%</td>
</tr>
</tbody>
</table>

*Energy per channel number in keV/unit
FLUX ATTENUATION FACTOR

ENERGY (keV)

DETECTOR A

DETECTOR B

FIGURE 3
Detector Resolution

Detector B

Detector A

FWHM Percent Resolution

Energy (keV)

Figure 4
The altitude measuring equipment included National Center for Atmospheric Research (NCAR) supplied aneroid devices. In addition, a Metrophysics Corporation Model 103111 pressure transducer was used on Flight 1967-3.
A. Conversion of Count Rate to Isotropic Flux

For count rates from a given instrument to be meaningful, they must be converted into absolute flux units of the form

photons/unit area-unit time-unit solid angle-energy interval.

In addition to knowing the effective time, area, solid angle and energy interval, the efficiency and resolution must be taken into consideration.

The amount of viewing time is an easily measured quantity and the energy width can be determined from a channel number to energy calibration. The geometrical factor involving the detector area and solid angle is a non-trivial measurement for other than simple geometries.

The count rate, \( C(E) \), was transformed to absolute flux, \( f(E) \), by the following equation:

\[
f(E) = \frac{C(E)F(E)K(E)}{AWS(E)Eff(E)}
\]

where \( F(E) \) is the flux attenuation factor previously described, \( Eff(E) \) is the photo peak efficiency of the central crystal and \( K(E) \) is the correction for \( K \) X-ray escape from the central detector taken from the results of Axel, 1954. The photo peak efficiency was taken from the theoretical results of Miller, Reynolds, and Snow, (1957) and the experimental work of Neiler and Bell (1965). The total correction factors for efficiency, phototube absorption and \( K \) X-ray escape are given in Figure 6.
In the above equation, $A$ is the frontal area of the central crystal, and $S(E)$ is the effective solid angle. The effective solid was obtained by considering isotropic photon leakage through the guard crystal at various energies.

The effective solid angle was determined by two methods and the results were compared to allow a rough estimation of the error. The first method used the angular response measured by placing sources with known energy levels at measured angles from the axis of the detector. The second method used the angular response calculated by assuming exponential attenuation of the gamma-ray beam in the guard crystal. The measured angular response for three energies is given in Figure 7. The calculated transmission is

$$T(E, \theta) = e^{-X(\theta) \tau(E)}$$

where $T(E, \theta)$ is the transmission at energy $E$ and angle of $\theta$ from the detector axis, $X(\theta)$ is the path length, and $\tau(E)$ is the absorption coefficient. The effective solid angle is defined as

$$S(E) = 2\pi \int_{0^\circ}^{180^\circ} T(E, \theta) \sin \theta \, d\theta$$

for cylindrical geometry. The results of numerically integrating this equation using measured transmission values is given in Figure 8. Although this curve was drawn using three measured energies, the shape of the curve was obtained from the results of the calculation
EFFECTIVE SOLID ANGLE (STERADIANS)

EFFECTIVE GEOMETRY

ENERGY (keV)

FIGURE 8
using theoretical transmission values. The difference in effective solid angle obtained by measured and calculated transmission values was less than 20% at the three energies measured.
III. RESULTS

A. Ascent Data

Figure 9 shows the altitude profile obtained on Flight 1967-3 for three different energy ranges assuming an isotropic flux. Results of the other flights confirmed these data. The range \( e^{-1} \) attenuation depth of the highest energy radiation recorded is less than 10 g/cm\(^2\). The assumption of isotropy below this altitude should be valid except at very high altitudes where an isotropic effect may take place at about 10 g/cm\(^2\) depth. Brini, Ciriegi, Fuligni, and Morretti (1967) have experimentally verified the isotropy by flying upward and downward aimed detectors.

The depth of the maximum (55-65,000 ft. or 58-92 g/cm\(^2\)) is the same for all energy ranges within the altitude resolution and is in agreement with that obtained by Brini, et al. (1967) at a slightly higher latitude. The solid lines are the results of fitting a curve to the data. The form of the curve is described later.

Figure 10 is a graph of ionizing radiation as a function of altitude obtained on Flight 1967-2 (19 days before Flight 1967-3). Also represented is data taken in 1958 by Anderson (1961a) at the same geomagnetic latitude. The close agreement is further confirmed by Anderson (1961b) where the altitude of the maximum count rate of a Geiger-Muller tube was observed to be at 50 g/cm\(^2\), or 68,000 feet at a slightly higher latitude.

Comparison of Figures 9 and 10 indicate that the gamma-ray maximum and the ionizing radiation maximum lie
GAMMA RAY ALTITUDE PROFILE (FLIGHT 1967-3)

FLUX (photons/cm²-sec-keV-ster)

ALTITUDE (m.b.)

FIGURE 9
ION CHAMBER DATA

ION RATE  sec-cm$^3$-atm of STP air

-ANDERSON, 1961a
-FLIGHT, 1967-2

ALTITUDE (mb.)

FIGURE 10
within 3,000-13,000 feet or 8-42 g/cm^2 of each other with the gamma-ray maximum lying below the maximum recorded by the ion chamber. It should further be noted that both the ion chamber count rate maximum and the gamma radiation count rate maximum are very broad peaks on the order of 40 g/cm^2 wide.

Figures 11 through 24 give the spectrum of the gamma-radiation from 280 mb. to 3.5 mb. The change in shape of the spectrum is indicated by the "color indices". The color indices A, B, and C are defined to represent the relative importance of the counts between energies of 30-100 keV, 100-250 keV, and 250-560 keV. A, B, and C are defined as follows:

A = flux between 30-100 keV/flux between 250-560 keV
B = flux between 100-250 keV/flux between 250-560 keV
C = flux between 30-100 keV/flux between 100-250 keV

The "color indices" for different altitudes are plotted in Figure 25.

A curve of the form \( f(p,E) = A(E) \pm B(E)e^{-p/D(E)} \)

where \( p \) is the pressure and \( f(p,E) \) is the isotropic flux, appears to fit the data reasonably well. The positive sign was used for data below the maximum and the negative sign for data above the maximum. The results of a least square fit to the data between 5.1 mb and 52 mb is given in Table 3. The results of a fit to data between 102. mb and 710. mb is given in Table 4. These curves are represented graphically along with the data in Figure 9.
GAMMA RAY SPECTRUM
ALTITUDE 280. MB

FLUX (PHOTONS/SEC-CM²-STER-KEV)

10^0
10^-1
10^-2
10^-3
10^-4

ENERGY (keV)
10
100
1000

FIGURE 11
GAMMA RAY SPECTRUM
ALTITUDE 175 MB

FLUX (PHOTONS/SEC-CM^2-STER-KEV)

10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}

ENERGY (keV)

10 100 1000

FIGURE 12
FLUX (PHOTONS/SEC-CM² - STER - KEV)

GAMMA RAY SPECTRUM
ALTITUDE 115 MB

ENERGY (keV)

FIGURE 13
GAMMA RAY SPECTRUM
ALTITUDE 74. MB

FIGURE 14
GAMMA RAY SPECTRUM
ALTITUDE 48. MB

FLUX (PHOTONS/SEC-CM²-STER-KEV)

ENERGY (keV)

FIGURE 15
GAMMA RAY SPECTRUM
ALTITUDE 34 MB
GAMMA RAY SPECTRUM
ALTITUDE 23 MB

ENERGY (keV)

FLUX (PHOTONS/SEC-CM^2-STER-KEV)

10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}

10 100 1000

FIGURE 17
GAMMA RAY SPECTRUM
ALTITUDE 16. MB

ENERGY (keV)

FLUX (PHOTONS/SEC-CM²-STER-KEV)
GAMMA RAY SPECTRUM
ALTITUDE 12 MB

FLUX (PHOTONS/SEC-CM²-STER-KEV)

EN Perkins (keV)

FIGURE 19
GAMMA RAY SPECTRUM
ALTITUDE 9. MB

FIGURE 20
GAMMA RAY SPECTRUM
ALTITUDE 6.3 MB

FLUX (PHOTONS/SEC-CM²-STER-KEV)

ENERGY (keV)

FIGURE 21
Figure 22

Gamma Ray Spectrum
Altitude 4.7 MB

Energy (keV)

Flux (Photons/sec-cm²-ster-keV)
FLUX (PHOTONS/SEC-CM²-STER-KEV)

GAMMA RAY SPECTRUM
ALTITUDE 4.1 MB

ENERGY (keV)

FIGURE 23
GAMMA RAY SPECTRUM
ALTITUDE 3.5 MB

FLUX (PHOTONS/SEC-CM²-STER-KEV)

ENERGY (keV)

FIGURE 24
"COLOR INDICES"

- $A = \frac{F(30-100 \text{ keV})}{F(250-560 \text{ keV})}$
- $B = \frac{F(100-250 \text{ keV})}{F(250-560 \text{ keV})}$
- $C = \frac{F(30-100 \text{ keV})}{F(100-250 \text{ keV})}$

ALTITUDE (mb.)
Table 3

Results of Fitting the Equation
\[ f(p,E) = A(E) - B(E)e^{-p/D(E)} \]
between \( p = 52 \) to \( p = 5.1 \) mb

<table>
<thead>
<tr>
<th>Energy Range (keV)</th>
<th>( A(E)* )</th>
<th>( B(E)* )</th>
<th>( D(E) ) (mb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-100</td>
<td>453.2</td>
<td>361.0</td>
<td>36.0</td>
</tr>
<tr>
<td>100-250</td>
<td>171.8</td>
<td>156.0</td>
<td>63.3</td>
</tr>
<tr>
<td>250-564</td>
<td>63.9</td>
<td>61.1</td>
<td>54.2</td>
</tr>
</tbody>
</table>

*Units of \( 10^{-4} \) photons/cm\(^2\)-sec-ster-keV

Table 4

Results of Fitting the Equation
\[ f(p,E) = A(E) + B(E)e^{-p/D(E)} \]
between \( p = 710 \) to \( p = 102 \) mb

<table>
<thead>
<tr>
<th>Energy Range (keV)</th>
<th>( A(E)* )</th>
<th>( B(E)* )</th>
<th>( D(E) ) (mb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-100</td>
<td>5.10</td>
<td>782.8</td>
<td>139.1</td>
</tr>
<tr>
<td>100-150</td>
<td>3.11</td>
<td>221.6</td>
<td>140.3</td>
</tr>
<tr>
<td>250-564</td>
<td>.96</td>
<td>101.8</td>
<td>113.2</td>
</tr>
</tbody>
</table>

*Units of \( 10^{-4} \) photons/cm\(^2\)-sec-ster-keV
B. **Float Data**

Before analyzing the spectrum and the major causes of the atmospheric gamma radiation at balloon float altitudes (about 3.5 mb) it would be appropriate to consider the effects not dependent on the atmosphere itself, but which have a measurable effect on the count rate.

In order to analyze the changes in the count rate it is necessary to separate the effects causing the change. The first order effects are postulated to be a zenith angle dependence due to a constant isotropic celestial gamma-ray flux and the magnetic field cutoff of the cosmic radiation responsible for the atmospheric gamma-rays.

The celestial background flux effect is dependent on the balloon altitude since the radiation is rapidly absorbed with atmospheric depth. Since the detector only measures the total of atmospheric and attenuated celestial background, it is not possible to separate the two. However, by fitting a power law to the isotropic background data found in Fazio (1967), it is possible to estimate the flux at the telescope due to this radiation. The power law is found to be

\[ \frac{dN}{dE} = 30 E^{-2} \]

where \( E \) is in keV and \( dN/dE \) is in photons/cm\(^2\)-sec-ster-keV. Knowledge of the extraterrestrial component at the telescope allows evaluation of the ratio of celestial background to total measured background. Figure 26 shows this ratio for Flight 1967-3 at an altitude of 3.9 mb. The zenith angle dependence shown is based on the assumption that the path length is proportional to the secant of
PERCENT EXTRATERRESTRIAL CONTRIBUTION TO TOTAL FLUX AT 3.9 MB.
the zenith angle. By integrating over the whole energy range the total count ratio for the entire energy range may be evaluated; it is given as a function of zenith angle in Figure 27.

The other postulated major effect on the count rate is the magnetic field cutoff of the cosmic radiation responsible for the atmospheric component. The dip latitude of the balloon for Flight 1967-3 varied from about 41° to 43 ½°. The count rate at different latitudes, both uncorrected and corrected for the zenith angle dependence described above, yields the atmospheric gamma-ray background as a function of latitude which is shown in Figure 28. The solid line is proportional to the number of ion pairs produced by ionizing radiation but has been conveniently normalized for the purpose of this graph (Neher and Anderson, 1962).

To obtain a spectrum at float altitude the assumption of isotropy must be made. For the entire energy range it appears that the extraterrestrial flux will account for about a 25% greater flux from the upward direction (See Figure 27). However, this effect is apparently dominated by considering the finite source thickness when looking upward which causes an isotropy of as much as 30% in the downward direction at 300 keV and less at other energies (Frost, Rothe, and Peterson, 1966). An estimation of the error caused by the anisotropic effect would be 10% or less at most energies. The error due to anisotropy must be added to the 20% error previously estimated for the solid angle corrections.
PERCENT EXTRATERRESTRIAL FLUX AT 3.9 MB (30–570 keV)

Figure 27
COUNT RATE VARIATION WITH LATITUDE
(30–570 keV)

NOT CORRECTED  CORRECTED TO 0° Z.A.
FOR ZENITH ANGLE
VARIATION

(Standard Deviations on this Scale are Negligible)

Proportional to Ionizing Radiation (See Text)
The measured background spectrum at float altitude is given in Figure 29. This was obtained from Flight 1967-3 during the background pointing segments of the flight. The zenith angle varied from $50^\circ$ to $13^\circ$ and the altitude varied no more than 0.3 mb from 3.9 mb, based on the pressure transducer data. The aneroid devices verified that the altitude was between 3.5 and 4.5 mb.

The background spectrum appears to follow a power law of the form

$$f(E) = AE^{-\gamma}$$

where $f(E)$ is the differential flux in units of photons/cm$^2$-sec-ster-keV and $E$ is in keV. A least squares fit between 35 and 160 keV yields values for $A$ and $\gamma$ of 27.77 and 1.87, respectively. By assuming a continuation of this power law spectrum a difference between the actual spectrum and the extrapolation of the power law can be made to reveal a possible line spectrum superimposed on the continuum. The results of this calculation are given in Figure 30.

Line features are present at 200 keV, 260 keV, and 490 keV. Shafroth (1967) has determined a peak at 204 keV due to fast neutron inelastic scattering of $^{127}$I. He also observes three peaks at 396 keV, 441 keV, and 490 keV which form an unresolved peak similar to the one shown in Figure 30. The peak at 396 keV is probably due to inelastic scatter of $^{127}$I, the peak at 441 keV due to inelastic scatter of $^{127}$I or Na$^{23}$, and the peak at 490 keV is unexplained. The peak at 260 keV is present in all past flights, but has not been observed by Shafroth (1967).
FLUX (PHOTONS/SEC-CM²-STER-KEV)

GAMMA RAY SPECTRUM
ALTITUDE 3.9 MB

ENERGY (keV)

FIGURE 29
EXCESS COUNTS

COUNT RATE (Arbitrary Units)

ENERGY (keV)

FIGURE 30
It appears too sharply defined and at too high an energy to be attributed to backscattering in the atmosphere or the instrument.
C. **Background Increase**

During Flight 1967-1 an apparent increase of approximately 30% was observed in the counting rate. This increase took place within the period of thirty minutes.

Before an explanation of the background increase is attempted, the following information should be considered. The counting rate for three different energy ranges vs. time is given in Figure 31 in two minute intervals. This must be considered in view of Figure 32 which gives the separation of the Crab Nebula and the Sun from the axis of the telescope as a function of time. The pattern of the graph until 1:58 CDT is due to a twenty minute pointing-offset period necessary to separate the contribution from the Crab Nebula. At 1:58 CDT the azimuth pointing servo motor failed and the free azimuth rotation of the telescope caused it to have the indicated separation from the Crab Nebula and the Sun.

In an attempt to explain the background increase, several of the most likely possibilities will be considered:

1) **Equipment Failure** - Only one monitor of the pulse-height analysis system, including photomultiplier tube regulating voltages, indicated that the equipment was not operating properly. A post flight calibration also showed no change in the pulse-height analysis system. The single negative indication was from the "reject rate", which is a scaled count of the number of pulses rejected by the anti-coincidence system. However, evidence strongly indicates that this was a failure in the telemetry equipment rather than the actual reject circuitry because the
COUNT RATE VS. TIME
(Flight 1967-1)

250-560 keV

100-250 keV

30-100 keV

COUNT RATE (Counts/2 Minutes)

TIME (CDT)

FIGURE 31
POINTING HISTORY
(FLIGHT 1967-1)
indications of the reject trouble were not confirmed by changes in the count rate. Also, no correlation can be made between the time of the increase and the time of the reject failure. Although equipment failure cannot be ruled out completely, no evidence points directly to this conclusion.

2) Crab Nebula - Since the count rate seems to increase in the general direction of the Crab Nebula this may seem to be a likely candidate. However, this would imply that the gamma ray output of the Crab Nebula could vary by a factor of 2.5 within thirty minutes. This possibility seems improbable since no other observations have indicated time variations in the Crab Nebula.

3) Atmospheric Background - A large change in the atmospheric background would indicate that either the cosmic radiation or the isotropic celestial background had varied rapidly. The cosmic ray constancy in time is considered extremely stable within a few percent (Hooper, 1964). No time variation in the cosmic diffuse gamma radiation was reported in a 40-hour Ranger 3 flight (Arnold, Metzger, Anderson, and Van Dilla, 1962). Also, the anisotropic increase which we observed seems to rule out an isotropic background increase.

4) Solar Gamma Ray Flare - The most likely source of the gamma-ray increase is the sun. The source seems to originate in the area of the sun's position. Various authors have previously reported hard x-ray and soft gamma-ray fluxes which they attributed to direct output by the sun (deJager, 1967; Arnoldy, Kane and Winckler,
The ion chamber data confirms the assumption that the increase in count rate is not a background increase and that it is due purely to an increase in the gamma-ray flux. The ion rate is plotted in Figure 33 as a function of time throughout the flight. The ion rate increase is about 5 ion pairs/sec-cm\(^3\) STP air during the gamma-ray increase. If the gamma-ray increase had been associated with charged particle radiation a much larger change (approximately 30\%) in the ion rate would have been observed.

By assuming that the increase may be attributed entirely to the sun, it is possible to evaluate the photon flux. A "solar flux" was obtained by subtracting the previous background and Crab Nebula gamma radiation from the data obtained from 1:20 to 1:30 CDT and from 1:40 to 1:50 CDT. Recorrecting this difference for the angular response of the detector, because the sun was not on the axis, and for atmospheric absorption, a count rate is obtained. This count rate is given in units of photons/cm\(^2\)-sec-keV in Figure 34. The power law, \(f(E) = 43.1 E^{-1.75 \pm 0.05}\) photons/cm\(^2\)-sec-keV, (where E is in keV) provides a good fit to the data. The response of the ion chamber to this flux would be negligible based on a rough calculation using the results of Anderson, Despain, and Neher (1967). The ion chamber increase is accounted for by the change in geomagnetic latitude. Neher (1967) indicates a coefficient of approximately 9 ion pairs/sec-cm\(^3\) STP air per degree of geomagnetic latitude. The balloon drift which caused a
SOLAR FLARE SPECTRUM

FLUX (photons/cm²-sec-keV)

ENERGY (keV)

\[ F(E) = 4.31E^{-1.75} \]

FIGURE 34
\( \frac{1}{2}^\circ \) to 1\(^\circ\) change in geomagnetic latitude is probably responsible for the entire ion rate change observed.
IV. CONCLUSIONS

The problem of analyzing the atmospheric gamma-ray spectrum at a given altitude is extremely difficult. The problem consists of evaluating gamma radiation incident from other altitudes in addition to gamma radiation produced by various mechanisms and gamma radiation absorbed by other processes. It is generally thought (e.g., Perlow and Kissinger, 1951; Peterson, 1963) that the gamma ray spectrum below 500 keV is due primarily to photons produced by the bremsstrahlung of higher energy electrons and the subsequent Compton scattering of these photons, with a possible contribution from the annihilation of positrons. Another process which produces gamma-rays is the decay of π° mesons produced in primary cosmic ray interactions. Radioactive isotopes produced by cosmic ray interactions, thermal neutron capture, or inelastic neutron scattering can also contribute to the gamma-ray flux. Celestial sources, or any other source of high energy photons or electrons, may produce an electron-photon cascade. Cascades are generally initiated by electrons or photons with energies greater than 100 MeV.

In equilibrium with the production of gamma radiation are processes which remove gamma rays from the atmosphere. The major loss mechanisms are pair production, Compton scattering, and photoelectric absorption. Above 20 MeV a photon in air will most likely be absorbed by the process of pair production which creates an electron and a positron. Unless the electron and positron are extremely energetic,
they will be stopped in the atmosphere without further radiative loss. A photon between 0.1 and 20 MeV will most likely Compton scatter giving part of its energy to an electron and resulting in a lower energy photon. This photon gradually loses energy until it gets below about 0.1 MeV where photoelectric absorption removes the photon from the flux.

The problem of monoenergetic source gamma-rays interacting with matter is a difficult one to solve. In the case of atmospheric gamma radiation, the source functions are not well understood. The problem of gamma radiation in the atmosphere has not been successfully solved on a theoretical basis. Due to the lack theoretical results, it is impossible to explain in detail the variation in shape or in magnitude of the spectrum with altitude.
A. Ascent

It may be concluded from Figure 25 that the gamma-ray spectrum does change shape as the altitude changes. Although these changes are difficult to explain in detail (due to the complexity of the processes involved), some conclusions may be drawn.

The method of fitting curves of the form $f(p,E) = A(E) + B(E)e^{-p/D(E)}$ to the count rate $f(p,E)$ was applied to smaller energy ranges than those shown in the previous section. The spectrum was divided into 34 keV wide intervals and curves of the above form were fitted by a least squares procedure. The results of fitting the curve $f(p,E) = A(E) + B(E)e^{-p/D(E)}$ below the maximum are given in Figure 35 to indicate the energy dependence of $A$, $B$, and $D$. Similarly the results of fitting the curve $f(p,E) = A(E) - B(E)e^{-p/D(E)}$ to data above the maximum are given in Figure 36.

The curve used to fit data below the maximum, $f(p) = A + B e^{-p/D}$ may be given the physical interpretation of being the sum of radiation due to a hard component, $A$, which is independent of depth and a soft component, $B$, where the soft component is attenuated in an absorption length, $D$. The terms hard and soft component refer to the relative absorption lengths of the gamma radiation producing component. A large absorption length would indicate an almost uniform magnitude dependence on the altitude. It is apparent from Figure 35 that the amplitude of the hard component is much smaller than that of the soft component, but the absorption length is
ENERGY DEPENDENCE OF A, B, AND D

WHERE

\[ f(p,E) = A(E) + B(E) e^{-p/D(E)} \] (below maximum)

ENERGY (keV)

\[ A(\text{photons/cm}^2\text{-sec-ster-keV}) \]

\[ = A \]

\[ = B \]

\[ = D \]

\[ D(\text{gm/cm}^2) \]

\[ = 100 \]

\[ = 10 \]

\[ = 1 \]

\[ = 10^{-3} \]

\[ = 10^{-2} \]

\[ = 10^{-1} \]

\[ = 10^{-0} \]

\[ = 10^{5} \]

\[ = 10^{2} \]

\[ = 10^{1} \]

\[ = 10^{-3} \]

\[ = 10^{-2} \]

\[ = 10^{-1} \]

\[ = 10^{-0} \]

ENERGY (keV)

FIGURE 35
ENERGY DEPENDENCE OF A, B, AND D
WHERE \[ f(p, E) = A(E) - B(E) e^{-p/D(E)} \] (above maximum)

\[ \text{D(gm/cm}^2) \text{/cm}^2 \text{-sec-ster-keV} \]

\[ \text{A & B (photons/cm}^2 \text{-sec-ster-keV)} \]

\[ \text{ENERGY (keV)} \]

\[ \text{FIGURE 36} \]
somewhat in doubt. Most of the data points indicate that the absorption length of the gamma radiation is closer to the 123 g/cm$^2$ associated with the soft component (Puppi and Dallaporta, 1952), than the fast neutron absorption length of 169 g/cm$^2$ (Haymes, 1964). The relative increase in the hard component amplitude, A, at about 200 keV may be due to neutrons producing a 203 keV line in the central detector. The neutron production will be discussed later.

Fitting the data to a curve of the form $f(p) = A - Be^{-P/D}$ above the maximum has little physical significance; however, it gives a good empirical fit to the data, and allows comparison with Brini, Ciriegi, Fuligni, Gandolfi, and Moretti (1965). Whereas Brini, et al., (1965) indicated no energy dependence of the constants A, B, and D, the data in Figure 36 indicates a very definite energy dependence of A and B. Also, the average value of D appears to be between 50-60 g/cm$^2$ versus approximately 30 g/cm$^2$ shown by Brini, et al., (1965).

Our data are consistent with the assumption that the gamma radiation is primarily associated with the bremsstrahlung of atmospheric electrons produced by \( \pi^0 \) decay from cosmic ray interactions. In a simple cascade model of an electromagnetic shower (Heitler, 1954) an electron of initial energy, $E_o$, incident on an absorber of thickness, $X_o$ (a cascade unit), will radiate a photon of energy, $E_o/2$, and retain an energy, $E_o/2$, at the end of this thickness. After another thickness, $X_o$, the electron releases a photon of energy, $E_o/4$, and retains an energy of $E_o/4$ and the photon produced earlier will create an electron
pair, each having an energy of $E_o/4$. This process will take place until the electron gets to an energy $E_c$ which is the critical energy below which ionization, rather than radiation, dominates the energy loss of the electron. At this point, the shower will have produced a maximum number of particles and gamma rays. $E_c$ is 84.2 MeV in air (Rossi, 1952).

Figure 37 is a schematic representation of the postulated process causing the gamma ray maximum. The majority of particles emitted from a nuclear star are grey particles which include pions with energies less than 500 MeV (Camerini, et al., 1950). The charged pions rapidly decay into charged muons which travel about 75 km, or through the rest of the atmosphere, before decaying into electrons (Anderson, 1967). The neutral pions, however, decay almost immediately into two gamma-rays with energy less than 300 MeV. At a distance of approximately one cascade unit, $X_\circ$, these gamma-rays produce an electron-positron pair with an energy of 150 MeV. At the end of the second cascade unit, $2X_\circ$, the electrons emit photons with energies of about 75 MeV, leaving electrons with energies of approximately 75 Mev which is below $E_c$ and thus radiation becomes less important.

The gamma-ray production maximum is thus expected to be on the order of one or two cascade units below the ionizing particle maximum. One cascade unit, 37 g/cm$^2$ in air, is about 14,000 feet below the ionizing radiation maximum. The neutral pion emitted from the
nucleus is not always emitted in the incident direction and this effect would cause the gamma-ray maximum to be an even smaller distance below the charged particle maximum. Data from this experiment are consistent with the assumption that the large gamma-ray flux at the production maximum is then Compton scattered isotropically into the 30-560 keV energy range at about the same altitude.

It should be pointed out that this model is a gross simplification of the actual situation. It is consistent, however, with the work of various authors. Carlson, Hooper, and King (1950) have determined a gamma-ray spectrum due to π° decay and have derived a maximum at 150 MeV. Brini, et al., (1967) and Anderson (1961b) have come to essentially the same conclusion, i.e., the gamma rays are primarily associated with the electron component in the atmosphere. At low energies where electron radiation ceases to be important, cascade theory has not been worked out in detail. Therefore, it is not possible to make further comparison of data with theory.
B. **Line Features**

From data shown in the Results section (Figure 30) it is apparent that neutrons have an effect which cannot be ignored when attempting to observe a line spectrum or even a continuum spectrum. In view of the important feature at 490 keV it is worthwhile to see how this may affect attempts to observe a 511 keV annihilation line.

The only neutrons causing inelastic scatter gamma-rays are those which do not interact with the guard crystal. By using the total cross section for neutron absorption from Adair (1950) and assuming that a neutron must travel the total average dimension of the detector, the transmission of neutrons is roughly 10%. Assuming a 10% transmission of the neutron flux calculated by Lingenfelter (1963) and using the .203 MeV inelastic scattering cross section given by Lind and Day (1961) the instrument should measure approximately 0.28 counts/sec. This is in good agreement with the 0.31 counts/sec at 203 keV measured at float altitude during Flight 1967-3. The calculated count rate at 440 keV due to inelastic neutron scattering also appears to be in agreement with the measured fluxes.

A possible explanation for the fact that previous investigators have not reported lines at 203 keV (Peterson, 1963; Peterson, Jacobson, and Pelling, 1966; Chupp, *et al.*, 1967) lies in the geometry and detector thickness. Peterson (1963) and Chupp, *et al.*, (1967) acquired data with small crystals in a phoswich configuration which had a small path length for neutron scattering.
Even more important is the fact that their large solid angle allows approximately 60 times the gamma-ray count rate of the Rice instrument. However, the Rice detector attenuates the neutron beam by only a factor of 10. Therefore, the phoswich gamma-ray count rate to neutron count rate should be at least 6 times that of the directional detector at 203 keV.

A collimated instrument with a thin detector such as Peterson, et al., (1966) is also less likely to respond to neutrons because of the small path length. Their detector thickness was only .5 cm and should result in a count rate of 1/10 the count rate of the Rice detector for the 203 keV line (assuming equal neutron absorption in their shield).

The features at 260 keV and 490 keV remain unexplained. The apparent line at 260 keV may possibly be due to backscatter of photons with energies in excess of 2.5 MeV. However, it is difficult to understand how a continuum could produce such a well defined line feature. Neutron production of the feature at 260 keV seems unlikely since the feature does not appear when a plutonium beryllium neutron source is placed beside the detector and such a feature has not been observed by others working with NaI(Tl) detectors in the laboratory (Shafroth, 1967). A thorough survey of elements in the vicinity of the detector during flight indicates no likely source of 250-270 keV gamma-rays (Nuclear Data Tables, 1960).

Although a feature at 490 keV has been observed before (Shafroth, 1967) its origin has not been determined.
The strength of the 490 keV peak is much less than that of the 440 keV peak observed by Shafroth (1967) and the 490 keV peak is not apparent when a neutron source is placed beside the detector. It can be seen in Figure 29 that at float altitudes the 490 keV peak is the most prominent feature above 400 keV. Thus, it is not likely that this feature is due to the effects of neutrons in the detector. Nor do any other elements likely to be around the detector have observed lines around 490 keV.

Although the presence of a 511 keV line has been reported by Peterson (1963) and Chupp, et al., (1967) it is possible that they were observing a different feature similar to the one observed during the Rice flights. While it may be reasonable to assume a feature at 511 keV, it has not been shown to exist. Peterson's (1963) apparatus had a channel width of approximately 40 keV which is not sufficient to differentiate between a peak of 490 keV and 511 keV. Data given by Chupp, et al., (1967) indicates a peak at least 30 keV above 511 keV.

It is possible that the features around 500 keV observed by Peterson (1963) and Chupp, et al., (1967) are due to the line observed at 490 keV during the Rice flights. Chupp, et al., (1967) suggests that the 500 keV feature may be due, at least in part, to nuclear bomb debris; specifically they cite the $^{103}$Rh$^{103}$ decay, resulting in a 490 keV photon. They also suggest the possibility of a 480 keV photon from Be$^{7}$ produced by cosmic ray interactions in the atmosphere.
Based on data taken at approximately 3.9 mb, an upper limit of $0.45 \pm 0.09$ photons/cm$^2$-sec can be put on a possible 511 keV line. However, this upper limit is based on the assumption that the 511 keV line is responsible for all of the counts seen at this energy. The actual value is probably much smaller because of the contribution from the unresolved 490 keV peak and the continuum. A fairly conservative estimate to the upper limit would be closer to $0.2$ photons/cm$^2$-sec. If the feature at 490 keV is due to a single line in the atmosphere, then the line strength is $0.5 \pm 0.1$ photons/cm$^2$-sec. These fluxes may be compared to $0.29 \pm 0.04$ photons/cm$^2$-sec measured by Chupp, et al., (1967) and $0.31 \pm 0.03$ photons/cm$^2$-sec measured by Peterson (1963) for the "500 keV" feature.

The use of high resolution solid state detectors may be necessary to fully resolve the problem of atmospheric line structure. Furthermore, the response of such detectors and surroundings to neutrons must be studied closely to insure an understanding of the resulting spectrum.
C. Solar Gamma Radiation

Because the evidence strongly suggests that the sun was responsible for the excess seen at the end of Flight 1967-1 on June 4, 1967, it is appropriate to state some conclusions based on the assumption that a solar gamma-ray flare was responsible for the enhanced flux beginning at 1820 UT and that the sun was not important before this time. The small chance that these assumptions are not valid is outweighed by the possibility of gaining much greater insight in the area of high energy photon emission from the sun.

The major doubt as to the validity of the results is that such a phenomenon has not been observed previously. However, this is not unreasonable when it is realized that the instrument flown was of considerably greater sensitivity than that of other instruments in a position to observe this activity. The only other attempt to observe gamma radiation with an instrument of comparable sensitivity was made at a time when solar activity was at a minimum (Frost, Rothe, and Peterson, 1966).

The main features of the solar gamma-ray flare observed may be summarized as follows: The flare began between 1810 UT and 1820 UT on June 4, 1967, and lasted for at least 30 minutes. The spectral shape and magnitude of the flare remained constant within statistics as is evidenced by the data given in Figure 38. This makes the spectrum previously given in Figure 34 a valid representation for the entire twenty minutes of observation rather than just an average of possible time varying
Figure 38

SOLAR TIME VARIATION

COUNT RATE

TIME (CDT)

1:20  1:30  1:40  1:50

250-570 keV

100-250 keV

30-100 keV
spectra. The intensity of the flare is much greater than the upper limits observed for the quiet sun (Frost, Rothe, and Peterson, 1966) but much less than that observed previously for solar x-ray flares (Hudson, Peterson, and Schwartz, 1968; Chubb, Kreplin, and Friedman, 1966). The spectrum observed is definitely non-thermal and is best fit by the power law \( f(E) = 43.1 E^{-(1.75 \pm 0.05)} \) photons/cm\(^2\)-sec-keV. A two standard deviation upper limit of \( 1.96 \times 10^{-4} \) photons/cm\(^2\)-sec may be placed on a possible 511 keV line from the sun. The energy flux from the sun between 38 and 570 keV was \( 1.89 \times 10^{21} \) erg/sec assuming isotropic solar emission.

The duration of the flare is considerably longer than that usually observed (220 seconds for 12.5-22 keV X-rays (Hudson, Peterson, and Schwartz, 1968); 1 or 2 minutes for "deci-MeV" bursts summarized by deJager (1967)). The length of the gamma-ray flare cannot be determined exactly, but can be said to exist from 1820 to 1850 UT. These times appear to correlate with a normal brightness Subflare observed by the solar flare observatory at Haleakala, Hawaii, between 1822 and 1848 UT (CRPL, 1967). A Subflare is defined as optical brightness covering less than 100 millionths of the solar surface area. Although no microwave emission was observed at the time of the gamma-ray emission, radio energy of intensity 3, Type III, was observed between 11-41 Mhz at 1825 for 0.4 minutes (CRPL, 1967).

The spectral shape of the radiation observed is definitely nonthermal and thus not of the type observed by
Chubb, Kreplin, and Friedman (1966). The power law form of the spectrum is similar to that observed by Cline and Holt (1968) but the flare that they observed was shorter and more intense.
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