INFORMATION TO USERS

This material was produced from a microfilm copy of the original document. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the original submitted.

The following explanation of techniques is provided to help you understand markings or patterns which may appear on this reproduction.

1. The sign or “target” for pages apparently lacking from the document photographed is “Missing Page(s)”. If it was possible to obtain the missing page(s) or section; they are spliced into the film along with adjacent pages. This may have necessitated cutting thru an image and duplicating adjacent pages to insure you complete continuity.

2. When an image on the film is obliterated with a large round black mark, it is an indication that the photographer suspected that the copy may have moved during exposure and thus cause a blurred image. You will find a good image of the page in the adjacent frame.

3. When a map, drawing or chart, etc., was part of the material being photographed the photographer followed a definite method in “sectioning” the material. It is customary to begin photoing at the upper left hand corner of a large sheet and to continue photoing from left to right in equal sections with a small overlap. If necessary, sectioning is continued again — beginning below the first row and continuing on until complete.

4. The majority of users indicate that the textual content is of greatest value, however, a somewhat higher quality reproduction could be made from “photographs” if essential to the understanding of the dissertation. Silver prints of “photographs” may be ordered at additional charge by writing the Order Department, giving the catalog number, title, author and specific pages you wish reproduced.

5. PLEASE NOTE: Some pages may have indistinct print. Filmed as received.

Xerox University Microfilms
300 North Zeeb Road
Ann Arbor, Michigan 48106
WALRAVEN, George David, 1948-
MEASUREMENT OF THE LOW-ENERGY GAMMA
RADIATION FROM THE GALACTIC CENTER
REGION.

Rice University, Ph.D., 1976
Physics, astronomy and astrophysics

Xerox University Microfilms, Ann Arbor, Michigan 48106

© 1976

GEORGE DAVID WALRAVEN

ALL RIGHTS RESERVED
PLEASE NOTE:

Pages 102, 107, 134 and 137
not included in material re-
ceived from the Graduate School.
Filmed as received.

UNIVERSITY MICROFILMS
RICE UNIVERSITY

MEASUREMENT OF THE LOW-ENERGY GAMMA
RADIATION FROM THE GALACTIC CENTER REGION

by

DAVID WALRAVEN

A Thesis Submitted
in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Thesis Director's Signature:

[Signature]

Houston, Texas
April 1976
Dedicated to

Edward and Todd
ACKNOWLEDGMENTS

I would like to express my appreciation to the following individuals who assistance and encouragement has helped make this dissertation possible:

Dr. Robert C. Haymes, who, as the author's thesis advisor, has not only provided continuous guidance and support but has also been chiefly responsible for stimulating the author's interest in gamma-ray astronomy.

Dr. Charles Meegan for his work during the flight and advice on certain aspects of programming.

Albert C. Heath, who, as project manager, designed and built much of the instrumentation and whose untiring efforts made a successful flight possible.

Robert D. Hall and David H. Shelton for their work during the flight and in the laboratory.

Frank T. Djuth for his assistance in the data reduction process and for many informative discussions.

The research discussed herein was supported in part by the National Science Foundation through Grant Number MPS 73-04785.
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Flight 74-1 Housekeeping Words</td>
<td>22</td>
</tr>
<tr>
<td>II</td>
<td>Gamma-Ray Calibration Sources</td>
<td>37</td>
</tr>
<tr>
<td>III</td>
<td>Gamma-Ray Attenuation Coefficients in Air</td>
<td>71</td>
</tr>
<tr>
<td>IV</td>
<td>Spectral Features Near 500 keV</td>
<td>112</td>
</tr>
<tr>
<td>V</td>
<td>Galactic Center Spectral Lines</td>
<td>119</td>
</tr>
</tbody>
</table>
# FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gamma-Ray Attenuation Cross-Sections in NaI</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>Schematic Diagram of the NaI(TI) Detector Assembly</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>The Gondola and Detector Assembly</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>Block Diagram of the System Electronics</td>
<td>19</td>
</tr>
<tr>
<td>5</td>
<td>Block Diagram of the Telemetry Ground Station</td>
<td>25</td>
</tr>
<tr>
<td>6</td>
<td>Altimeter Calibration</td>
<td>31</td>
</tr>
<tr>
<td>7</td>
<td>Magnetometer Calibration</td>
<td>34</td>
</tr>
<tr>
<td>8</td>
<td>Energy Calibration: &quot;A&quot; Analyzer</td>
<td>39</td>
</tr>
<tr>
<td>9</td>
<td>Energy Calibration: &quot;B&quot; Analyzer</td>
<td>41</td>
</tr>
<tr>
<td>10</td>
<td>Flow Chart of the Data Reduction Process</td>
<td>46</td>
</tr>
<tr>
<td>11a,b</td>
<td>Uncorrected Source and Background Segment Count Rates: &quot;A&quot; Analyzer</td>
<td>53</td>
</tr>
<tr>
<td>12a,b</td>
<td>Uncorrected Source and Background Segment Count Rates: &quot;B&quot; Analyzer</td>
<td>56</td>
</tr>
<tr>
<td>13</td>
<td>Background Segment Pointing in Galactic Coordinates</td>
<td>59</td>
</tr>
<tr>
<td>14</td>
<td>Total Uncorrected Source and Background Count Rates: Flight 74-1, &quot;A&quot; Analyzer</td>
<td>62</td>
</tr>
<tr>
<td>15</td>
<td>Total Uncorrected Source and Background Count Rates: Flight 74-1, &quot;B&quot; Analyzer</td>
<td>64</td>
</tr>
<tr>
<td>16</td>
<td>Detector Orientation for Instrumental Absorption Measurements</td>
<td>78</td>
</tr>
</tbody>
</table>
FIGURES (con't)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Energy Dependence of the Instrumental Correction Factors</td>
<td>79</td>
</tr>
<tr>
<td>18</td>
<td>Instrumental Response to $^{22}$Na Calibration Source</td>
<td>83</td>
</tr>
<tr>
<td>19</td>
<td>GX1+4: Differential Spectrum</td>
<td>88</td>
</tr>
<tr>
<td>20</td>
<td>GX1+4: Differential Spectrum with Transitted Segments Deleted</td>
<td>92</td>
</tr>
<tr>
<td>21</td>
<td>GX1+4: 0.5 FWHM Flux Sums Below 1.0 MeV</td>
<td>96</td>
</tr>
<tr>
<td>22</td>
<td>Combined Spectra from the 1970 and 1971 Observations</td>
<td>99</td>
</tr>
<tr>
<td>23</td>
<td>Uncorrected Total Source and Background Count Rates, Flight 71-2</td>
<td>102</td>
</tr>
<tr>
<td>25</td>
<td>Galactic Plane: 0.5 FWHM Flux Sums Below 1.0 MeV for Three &quot;Source&quot; Segments</td>
<td>107</td>
</tr>
<tr>
<td>26</td>
<td>Orientation of the 4 kpc Ring Structure in Galactic Longitude</td>
<td>114</td>
</tr>
<tr>
<td>27</td>
<td>GX1+4: 1.0 FWHM Flux Sums Above 1.0 MeV</td>
<td>123</td>
</tr>
<tr>
<td>28</td>
<td>Galactic Center Background Differences at Line Energies</td>
<td>126</td>
</tr>
<tr>
<td>29</td>
<td>Galactic Center Background Zenith Angle Pair Differences</td>
<td>128</td>
</tr>
<tr>
<td>30</td>
<td>GX1+4 Source Data Grouped into Four Azimuth Bins at Line Energies</td>
<td>131</td>
</tr>
<tr>
<td>31</td>
<td>Galactic Plane: 1.0 FWHM Flux Sums Below 1.0 MeV, One &quot;Source&quot; Segment</td>
<td>134</td>
</tr>
<tr>
<td>32</td>
<td>Galactic Plane: 1.0 FWHM Flux Sums Above 1.0 MeV, One &quot;Source&quot; Segment</td>
<td>137</td>
</tr>
</tbody>
</table>
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.  INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II. INSTRUMENTATION</td>
<td>3</td>
</tr>
<tr>
<td>A. Detector</td>
<td>3</td>
</tr>
<tr>
<td>1. Gamma-Ray Interactions</td>
<td>3</td>
</tr>
<tr>
<td>2. Detector Configuration</td>
<td>7</td>
</tr>
<tr>
<td>3. Anti-Coincidence</td>
<td>11</td>
</tr>
<tr>
<td>B. Gondola</td>
<td>12</td>
</tr>
<tr>
<td>C. Electronics</td>
<td>16</td>
</tr>
<tr>
<td>III. FLIGHT 74-1</td>
<td>27</td>
</tr>
<tr>
<td>A. Observing Technique</td>
<td>27</td>
</tr>
<tr>
<td>B. Pre-Flight Calibrations</td>
<td>28</td>
</tr>
<tr>
<td>C. Flight History</td>
<td>42</td>
</tr>
<tr>
<td>IV. DATA REDUCTION</td>
<td>44</td>
</tr>
<tr>
<td>A. Initial Programs</td>
<td>44</td>
</tr>
<tr>
<td>B. Segment</td>
<td>48</td>
</tr>
<tr>
<td>1. Normalized Segment Count Rates</td>
<td>50</td>
</tr>
<tr>
<td>2. Background Segment Pointing</td>
<td>51</td>
</tr>
<tr>
<td>3. Total Source and Background Count Rate</td>
<td>60</td>
</tr>
<tr>
<td>C. Final Data Reduction Procedures</td>
<td>66</td>
</tr>
<tr>
<td>1. Background Subtraction</td>
<td>66</td>
</tr>
<tr>
<td>2. Atmospheric Absorption</td>
<td>68</td>
</tr>
<tr>
<td>3. Partial Residual Combination</td>
<td>73</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS (CONTINUED)

<table>
<thead>
<tr>
<th>IV. (Continued)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4. Instrumental Corrections</td>
<td>73</td>
</tr>
<tr>
<td>a) Instrumental Absorption</td>
<td>74</td>
</tr>
<tr>
<td>b) Intrinsic Efficiency</td>
<td>77</td>
</tr>
<tr>
<td>c) K X-ray Escape</td>
<td>81</td>
</tr>
<tr>
<td>5. Corrected Spectrum</td>
<td>84</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>V. RESULTS AND THEIR SIGNIFICANCE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Continuum</td>
<td>86</td>
</tr>
<tr>
<td>B. Gamma-Ray Lines</td>
<td>94</td>
</tr>
<tr>
<td>1. 0.5 MeV Feature</td>
<td>94</td>
</tr>
<tr>
<td>2. Nuclear Lines</td>
<td>120</td>
</tr>
<tr>
<td>C. Galactic Plane Spectral Features</td>
<td>129</td>
</tr>
<tr>
<td>D. Models</td>
<td>139</td>
</tr>
</tbody>
</table>

| VI. CONCLUSIONS                  | 143|
| REFERENCES                       | 145|
I. INTRODUCTION

Some of the more important problems in astrophysics concern the origin and distribution of cosmic rays, the synthesis of the elements and the explosive processes which can occur in the later stages of stellar evolution. To obtain specific information about some of these various problems effectively requires the data which only gamma-ray astronomy can provide. In the interaction of cosmic rays with the interstellar medium, the cosmic ray nuclei can be excited, resulting in the emission of nuclear gamma-rays. An analysis of this data with appropriate theoretical models can provide information on the low-energy cosmic ray spectrum in addition to yielding data on the distribution of cosmic rays in the Galaxy. Analysis of the nuclear line data can also provide data on the relative abundance of various nuclides.

Nuclear gamma-ray astronomy also provides the means to detect novae and supernovae which may have not been observed optically. Even more important, analysis of the gamma radiation from such events can enable one to determine the validity of the very complex theoretical models that have been developed to explain such events. Finally, gamma-ray astronomy also permits one to probe for the presence of highly condensed objects such as black holes, whose existence cannot be determined directly.
The nuclear regions of galaxies, with their extremely high stellar densities, provide ideal subjects for observational programs that seek to obtain information on the above phenomena. Due to its proximity, the central region of our own Galaxy must be considered one of the most rewarding subjects for investigations at gamma-ray energies. Previous observations of the galactic center region disclosed the presence of a spectral feature at an energy of $\sim 476$ keV. A larger and more sensitive detector was subsequently used to re-examine the galactic center region. The reduction and analysis of the data obtained during the 1974-1 flight with this improved instrument forms the substance of this dissertation.
II. INSTRUMENTATION

A. DETECTOR

1. GAMMA-RAY INTERACTIONS

The principle fundamental to the operation of the detector is the emission of optical photons by the scintillator crystal as a result of gamma-ray interactions with the constituent atoms. Photons in the energy range measured by the present experiment can interact with matter (i.e. the scintillator crystal) in three possible ways: photoelectric absorption; Compton scattering; and pair production.

In the first of these mechanisms, atomic electrons are ejected by the incident gamma-ray photon. Since the cross-section increases with the binding energy of the electron, K shell electrons have the greatest probability of ejection. The atomic electron is ejected with a kinetic energy equal to the initial energy of the gamma-ray less the K or L shell binding energy. The ejected electron distributes its kinetic energy in the vicinity of the interaction site through inelastic scattering. The vacancy created by the ejected electron results in the emission of an X-ray or an Auger electron.

The second possible interaction mechanism, Compton
scattering, occurs when the incident gamma-ray photon is scattered inelastically by an atomic electron. This process occurs when the binding energy of the electron is negligible compared to the energy of the incident photon. This is in contrast to photoelectric absorption where the energies are comparable. Compton scattering thus produces an energetic electron which may be ejected from the atom and a secondary photon of reduced energy.

The third type of interaction, pair production, can occur if the gamma-ray photon has an energy of at least 1.02 MeV and is in the presence of a coulomb field. The kinetic energy of the resultant electron-positron pair is just the incident photon's energy minus the threshold energy. The positron will rapidly annihilate in the singlet state producing two 0.511 MeV photons. If the energy of the incident gamma-ray is sufficiently great, the electron created by the interaction can produce bremsstrahlung.

Figure 1 depicts the attenuation cross-sections for gamma-rays in NaI as a function of energy for the above interaction mechanisms. In each of these mechanisms, the energy of the incident gamma-ray is eventually converted into excited atomic states whose decay is accompanied by the emission of optical photons. On the average, one optical photon is produced for every 300 eV of energy that is deposited in the crystal. These optical photons can then
Figure 1

Cross-sections for the interaction of gamma-rays with sodium iodide as a function of energy. The total cross-section is shown in addition to the ones for photoelectric absorption, Compton scattering, and pair production. Data from NBS circular No. 583.
PHOTON ATTENUATION CROSS SECTIONS FOR NaI

Figure 1
be detected by photomultiplier tubes. The magnitude of the output current from the photomultiplier tube is then directly proportional to the energy of the incident gamma-ray (assuming total energy deposition and no losses in the scintillator).

2. DETECTOR CONFIGURATION

The basic configuration of the gamma-ray detector assembly is shown in Figure 2. The detector consists of two major units - a central crystal and a collimator/guard composed of three separate crystals.

The central detector crystal is composed of NaI(Tl) and has a diameter of 15 cm with a thickness of 5 cm. The crystal is viewed by a single 7.5 cm diameter phototube with a bialkalai photocathode. The base of this tube was removed to help reduce the background count rate. The light pipe is composed of a thin acetate base \(7 \times 10^{-3} \text{cm}\) on which an aluminum surface layer was vacuum deposited. The cathode of the photomultiplier tube is located about 7 cm from the surface of the central detector crystal. This separation enables the tube to average over inhomogeneities in the light output from the central crystal, thus reducing the spread in pulse heights for incident monoenergetic gamma radiation.

Almost completely enclosing the central crystal is the group of three collimator crystals. These are also composed of NaI(Tl) and define a 13° field of view full width
Figure 2

Schematic diagram of the NaI(Tl) scintillation detector system. The guard and collimator crystals define a 13° FWHM field of view for the central detector crystal. The detector aperture is covered by a sheet of plastic scintillator, which with the guard and collimator crystals, provides complete $4\pi$ steradian protection against data contamination by charged particles. Both the plastic and the guard and collimator crystals are connected in anticoincidence with the central crystal. Not shown are the four photomultiplier tubes which observe the plastic, the six which observe the collimator crystal, and the nine which observe the guard crystal.
half-maximum (FWHM) for the central crystal. The minimum collimator thickness is 12 cm. This corresponds to approximately two mean free paths thickness for gamma-rays with an energy of 3 MeV. This is approximately the energy of maximum transparency for NaI. The crystals that compose the collimator are viewed by a series of 5 cm diameter photomultiplier tubes. Six view the front collimator while nine view the guard crystal.

The rationale for having such a comparatively thick collimator is the following. During the observation of possible celestial gamma-ray sources, the detector system is at an altitude of more than 120,000 ft. At these altitudes the terrestrial atmosphere is itself a source of gamma-rays due to cosmic ray interactions. Thus the detector system is immersed in a relatively isotropic flux of gamma-rays. In order to improve the signal/noise ratio for gamma-ray source observations, it is desirable to minimize the leakage rate i.e. gamma-rays that penetrate the collimator without interacting but that do interact in the central crystal. The collimator thickness in the present system represents a compromise between attenuation of the atmospheric background and payload weight limitations. It should be noted that NaI contributes to the background count rate due to its activation by cosmic ray interactions.
3. ANTICOINCIDENCE SYSTEM

In order to obtain an accurate gamma-ray spectral measurement, it is essential that only events where the total energy of the incident gamma-ray is deposited in the central crystal are counted. During photoelectric absorption a K or L shell X-ray or Auger electron may escape the crystal. In an interaction involving Compton scattering, some secondary, scattered photons may escape the crystal. In a pair production event the 0.511 MeV photons may escape as might a sufficiently energetic secondary electron. All such events which do not deposit full energy in the central detector crystal must be rejected. To realize this objective, the collimator and central detector are connected in anticoincidence. The use of such a system also permits the rejection of particles or gamma-rays that enter the central detector from outside the defined field of view. Such events can produce scintillations in both the collimator and central detector crystals. Since the resolving time of the detector electronics is \( \sim 1 \mu \text{sec} \), such closely spaced events are treated as simultaneous and therefore rejected. The use of an actively collimated system with anticoincidence also provides the capability to reject events produced in the central crystal by secondary electrons or other charged particles created by interactions in the collimator crystals. Because the crystals composing the system are of quite finite dimensions, the ideal of perfect rejection is not
attained. In particular there is a "leakage" count rate due to photons from outside the field of view which scintillate in the central detector but not in the collimator.

To provide complete $4\pi$ steradian protection against data contamination by charged particles, the detector aperture is covered by a thin sheet of plastic, 1/4" thick. This plastic is viewed by four photomultiplier tubes which are connected in anticoincidence with the one viewing the central detector crystal. The low density of the plastic together with the low atomic number of its constituent elements makes it an ideal material for the aperture covering. While being sensitive to charged particles, the plastic thus causes only a small attenuation of incident low-energy gamma-rays.

B. GONDOLA

The mechanical structure supporting the detector assembly and containing essential subsystems has two major components - the inner and outer gondolas. These structures are depicted in Figure 3. The inner gondola consists of a cradle with a fork-type equatorial mount in which the detector assembly is secured. The mounting of the detector is such that it can be rotated in declination and hour angle. A dc torque motor is used to drive the declination axis while a digital stepping motor is used to provide rotation about the polar axis. The mounting permits a
Figure 3

The mechanical structure of the inner and outer gondolas which provide support and pointing capability for the gamma-ray telescope. Not shown are the battery packs which are mounted on the outer gondola and provide power for the on-board electronics and pointing system.
SWIVEL JOINT

\( \frac{1}{4}'' \) DIA STEEL CABLES (4)

DECLINATION AXIS

ELECTRONICS BOX

R.A. AXIS

DETECTOR

INNER GONDOLA

13°

OUTER GONDOLA

ANTENNA

4 ft

BALLOON-BORNE SYSTEM
RICE UNIVERSITY

9 ft

Figure 3
tracking accuracy of approximately $\pm 1^\circ$. The inclination of the polar axis was adjusted using a metal wedge so that this axis would be parallel to the earth's rotation axis for the mean geographic latitude anticipated for the detector during the flight. The inner gondola is mounted so that it can rotate with respect to the outer gondola, thus permitting the detector to be rotated in azimuth as well as in declination and hour angle. In addition to serving as a mount for the detector, the inner gondola also contains the pulse-height analyzers, telemetry electronics, levelometer, altimeter, magnetometers, and the antenna.

The outer gondola serves primarily as a support structure for the inner gondola and mounts the various battery packs that supply power for the pointing systems and electronics. Seven 12-volt heavy duty car batteries in pressurized boxes were used. Power from the battery packs is transferred to the inner gondola by means of copper slip rings on the azimuth shaft of the inner gondola. The outer gondola is connected to a parachute by equal-tension steel cables from each of the four corner posts. The cables terminate in a rotating mount designed to decouple the outer gondola from the rotation of the balloon. Despite the use of this rotating mount, the outer gondola tends to be weakly coupled to the balloon's rotation. Some of this rotation is also transmitted to the inner gondola because of friction present in the inner/outer gondola mounting. To compensate for any such changes in the azimuthal orientation
of the detector, a chain drive powered by a digital stepping motor was employed. Magnetometers mounted on the inner gondola sensed the direction of the local geomagnetic field and drove the stepping motor in the direction required to maintain proper pointing. It should be noted that this servo magnetometer system was also used to rotate the detector in azimuth when changing from source to background observations or vice versa.

C. ELECTRONICS

The energy domain measured by the detector (15 keV to 12.2 MeV) was covered by two on-board pulse-height analyzers, each one having 256 channels. The design of the analyzers is quite simple in principle. The output from the photomultiplier tubes is a voltage pulse proportional to the light collected by the photocathodes. This pulse is then used to charge a capacitor whose decay time is measured by a 4.5 MHz oscillator. The number of completed oscillator cycles in the decay time gives the channel number in which the pulse will be registered. Each analyzer classified only events in the central crystal that were not rejected by the anticoincidence circuitry and in which the energy deposited was within the energy interval appropriate to that analyzer. The low-energy analyzer, designated "A", covered the region from 15 keV to 940 keV while the high-energy one, designated "B", spanned the 1 MeV to 12.2 MeV interval. The electronics are so arranged that if a
pulse-height it too large for the "A", it is automatically routed to the "B". Events in which the energy deposited is in excess of 12.2 MeV are counted and put into the first channel of the "B" analyzer.

To allow for closely spaced gamma-ray events (those less than 200 μsec apart), three storage registers are included to act as buffers. Figure 4 depicts the electronics for the two analyzers in block form. Once an event has been assigned to a pulse-height channel, the channel number is digitized into a 9 bit word and telemetered at a rate of 5000 bits/sec to the ground station where it is recorded on magnetic tape. Thus the system is limited to transmitting approximately 475 events/sec which represents a count rate that is at least an order of magnitude greater than that which is actually observed at a float altitude of ~125,000 ft.

Also recorded on magnetic tape at the ground station was the signal of the US radio station WWV. This was used to synchronize a commercial time code generator (accuracy 1 part in $10^8$ per day). The arrival of a digital word corresponding to the channel number of a gamma-ray event caused an interruption in the data flow such that the 7 least significant bits from the 36 bit time code generator word were added to the 9 bit word. Thus each gamma-ray event is represented by a 16 bit word which specifies channel number and time of arrival. The most significant
Figure 4

Block diagram of the on-board detector electronics showing the two 256 channel pulse-height analyzers. Each gamma-ray event in the central detector crystal that is not rejected by the anticoincidence circuitry is coded into a 9 bit binary word and presented to the telemetry system as an asynchronous PCM signal.
bits in the time code generator word are inserted into the
data stream between gamma-ray events.

In addition to the gamma-ray count data, 36 important
"housekeeping" voltages were digitized by the on-board
electronics into 10 bit words and telemetered at a rate of
$20 \times 10^3$ bits/sec. These various voltages provided knowledge
of the detector pointing, temperature, collimator count
rates, etc. and are listed in Table I. By using the house-
keeping decommutator, these values could then be viewed in
virtually real time.

A considerable amount of electronic equipment at the
telemetry ground station was necessary to receive, decode,
and record the data. The major components of the ground
station electronics are represented schematically in Figure
5. Of the various items of equipment used, three are
important enough to merit special note. All data were
recorded on analog tape using a 7-track Ampex tape recorder.
A Texas Instruments TI980A minicomputer with 8K memory was
used during the flight to monitor the status of the various
housekeeping parameters, accumulate spectra, and to compute
pointing corrections for the detector. The final item
worthy of note is the housekeeping decommutator, which
permitted display of selected housekeeping parameters in
real time. This proved invaluable not only in pointing
Table I.

The 36 housekeeping voltages that specify the status of key on-board systems. Each voltage was digitized into a 10 bit word and sampled 10 times/sec. These voltages could then be displayed on the housekeeping decommutator for real-time monitoring of the system.
TABLE I.

RICE UNIVERSITY
GAMMASCOPE VI
PCM COMMUTATOR

1. (TACH) TACHOMETER MONITOR

(8) 2. (MAG1) SERVO MAG #1
3. (MAG2) SERVO MAG #2
4. (12EB) + 12 V. MON. - EL. BOX
5. (-6EB) - 6 V MON - EL. BOX

(7) 6. (ALTI) ALTIMETER

(2) 7. (SLHA) SLOW HOUR ANGLE POT

(3) 8. (FSHA) FAST HOUR ANGLE POT

(4) 9. (SLDC) SLOW DEC. POT

(5) 10. (FSDC) FAST DEC. POT.

11. (E-W.) EAST-WEST LEVEL

12. (N-S.) NORTH-SOUTH LEVEL

13. (TORO) TORQUE MOTOR CURRENT

14. (DETT) DETECTOR TEMP.

(6) 15. (+HV.) CENTRAL HV MONITOR

16. (DPSW) DETECTOR PRESSURE SW.

(10)17. (REJC) REJECT RATE ÷256

(13)18. (CORN) COLLIMATOR RATEMETER

(12)19. (GURM) GUARD RATEMETER

(14)20. (RAHZ) R.A. FREQUENCY

(9) 21. (PERP) PERPENDICULAR MAG
TABLE I. (CONTINUED)

22. (28RG) + 28 V REG. MONITOR
23. (28BA) + 28 V BATTERY PACK MONITOR
24. (5REG) + 5 V. REG. MONITOR
25. (5BAT) + 5 V UNREGULATED
26. (EBXT) EL. BOX PRESSURE SW. & TEMP.
27. (GUAR) GUARD RATE / 40960
28. (COLR) COLLIMATOR RATE / 40960
(11)29. (CTHR) COLLIMATOR THRESHOLD
(15)30. (GTHR) GUARD THRESHOLD
31. (FRNT) FRONT HEATER MONITOR
32. (REAR) REAR HEATER MONITOR
33. (-6V.) -6 V MON. - PHA
34. (+12V) + 12 V MON. - PHA
35. (EHET) EL. BOX & RA MOTOR HEATER MON.
(1) 36. (GND.) GROUND.

Notes: Order for 15 words on mechanical commutator are in ( ).
Four character mnemonics for TT980A are in ( ).
Figure 5

Block diagram of the telemetry ground station. The equipment is arranged to receive and record gamma-ray pulse-height data, the arrival times associated with these events, and housekeeping voltages. Real-time display of the data permits monitoring and control of the experiment during the flight.
RUG-RAG GROUND STATION
RECEIVING / RECORDING SYSTEM

Figure 5
the detector at a celestial source but in determining whether telemetry commands were being received and acted upon by the on-board instrumentation.
III. FLIGHT 74-1

A. OBSERVING TECHNIQUE

In order to determine the spectrum of a celestial gamma-ray source it is necessary that both "source" and "background" gamma-ray data be accumulated. The background in the lower energy range of the detector (15 keV-300 keV) exhibits a zenith-angle dependence at float altitude. In addition the background count rates as determined by the detector display time dependence, with the counting rate gradually increasing as a function of time in certain parts of the spectrum. This phenomenon is due to relatively long-lived radioactive species created by cosmic ray interactions with NaI.

To deal with these problems a cyclic pattern of a 10 minute source observation followed by a 10 minute background observation was adopted. Such an observing technique tends to avoid coupling of zenith angle and time-dependent effects into the residual source spectrum. However, the 10 minute segment times are long enough so that enough counts are obtained to yield reasonably good statistics. Background segments were planned to be taken at azimuths 180° away from that at which the source observations were taken. Since the source was being tracked continuously by the
detector in hour angle it follows that the background segments do not lie in one particular region of the celestial sphere, but form a band across it. Consequently it is possible for discrete gamma-ray sources to be present in some of the background segments. This will be discussed in more detail subsequently.

B. PRE-FLIGHT CALIBRATIONS

Prior to launch of the gamma-ray detector system, a large number of instrumental calibrations were made. These were necessary in order that such things as detector pointing, altitude, temperature and analyzer gain be determined. Five of the most important calibrations will be discussed in some detail.

The gamma-ray axis determination was undertaken to define the relation of this axis to the optical or symmetry axis of the detector. Using a precision levelometer, the detector was leveled and oriented so that the projection of its symmetry axis was normal to the wall some 15 ft. distant. After locating the projection of this axis on the wall, a $^{57}$Co source was placed at successive points on the wall such that these points defined two mutually orthogonal axes centered on the projection point. For each location of the radioactive source, a spectrum and the peak counting rate were obtained. In this way plots of counting rate versus angular deviation were obtained. In addition to defining the relation of the gamma-ray axis to the optical axis, this
procedure also gave the angular response function of the
detector at the energy of the gamma-rays emitted by the
source. It should be noted that since the source was not
positioned at infinity with respect to the detector, a
point-source angular response function was not obtained.
However by extrapolating the results for angles greater
than $\pm 2^\circ$ off axis to angles smaller than this value, a
point-source like response was effectively obtained.

An on-board altimeter that measured the thermal
conductivity of the air was used to give knowledge of the
detector's altitude once float had been achieved. The
device is accurate to within 0.06 gm/cm$^2$ (about 300 ft.)
for altitudes above $10^5$ ft. The altimeter was calibrated
in a vacuum chamber. An oil manometer was used to deter-
mine the chamber pressure while the corresponding output
voltage was recorded. By tabulating the output voltage as
a function of pressure and hence altitude, the nonlinear
calibration curve depicted in Figure 6 was obtained.

To determine the pointing of the detector, knowledge
of the rotation about the polar and declination axes is
essential. On the instrument, each of these axes was
coupled to two potentiometers, one "slow" and the other
"fast" depending on the gear ratios. Both potentiometers
had the same voltage range but the difference in the gear
ratios caused many cycles of the fast pot to be present in
a single cycle of the slow one. The value of the slow pot
Figure 6

Altimeter calibration plot giving output voltage as a function of altitude. The altimeter measures the thermal conductivity of the air. For altitudes above 100,000 ft., the device is accurate to within 0.06 mb.
Figure 6

ATMOSPHERIC DEPTH [GM/CM²]

VOLTAGE
was thus used to determine which cycle the fast one was on. Then by using the value of the fast pot, the declination or hour angle could be determined to within \( \approx 1/4^\circ \). In the calibration procedure a precision levelometer was used with the fast and slow pot values being recorded for every \( 5^\circ \) change in angle.

The other quantity essential in computing the pointing of the telescope is the azimuth. Knowledge of this quantity is gained from two fluxgate magnetometers which measure the components of the geomagnetic field in a plane tangent to the earth's surface. Calibration was accomplished by first pointing the detector at true South. The three magnetometers mounted on the inner gondola were then rotated in the horizontal plane until the housekeeping voltage of the parallel magnetometers nulled. The magnetometers were then tightly secured in this position. This orientation thus gave the source pointing azimuth direction for the detector. The detector was then rotated 360° in 10° azimuth increments with the output voltages of the magnetometers being tabulated. The resulting calibration plot is shown in Figure 7.

Calibration of the two pulse-height analyzers was done on two occasions with the last such taking place just prior to launch. The calibration procedure involved accumulating a spectrum for each of a series of gamma-ray sources. For a given gamma-ray line energy, the response of the instrument was a photopeak of approximately gaussian shape centered
Figure 7

Flight 74-1 magnetometer calibration. Any azimuth orientation may be determined by a comparison of the parallel and perpendicular magnetometer housekeeping voltages.
on the line energy. For each photopeak the channel number corresponding to the peak counting rate was determined. In this way a series of channel numbers were identified with the corresponding source energies. The gamma-ray sources used in the calibration are listed in Table II. From these measurements, plots of energy versus channel number were prepared as shown in Figures 8 and 9 for the "A" and "B" analyzers, respectively. The gains of the two analyzers were found to be the following:

"A" analyzer: \( E(\text{keV}) = 14.6 + 3.61N \)

"B" analyzer: \( E(\text{MeV}) = 0.685 + 0.045(N-256) \)

where \( N \) is the channel number ranging from 1-256 for the "A" and 257-512 for the "B".

From the accumulated spectral data on the gamma-ray sources it was also possible to determine the energy resolution of each of the two analyzers. As noted previously, the detector response to a monoenergetic source of gamma-rays is a photopeak of roughly gaussian shape centered on the line energy. By convention the resolution is defined as follows:

\[
R(\%) = \frac{\Delta E_{\text{FWHM}}}{E_Y}
\]

where \( \Delta E_{\text{FWHM}} \) is the energy width of the photopeak measured at a counting rate that is half the peak counting rate and \( E_Y \) is just the energy of the incident gamma-ray. By
Table II.

Gamma-ray sources which were used in the determination of the gain and resolution for the "A" and "B" analyzers.
<table>
<thead>
<tr>
<th>Source</th>
<th>Photon Energy (MeV)</th>
<th>Peak Channel</th>
<th>FWHM* (Channels)</th>
<th>Resolution* (Percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{22}\text{Na}$</td>
<td>0.51</td>
<td>135.8</td>
<td>17.2</td>
<td>12.2</td>
</tr>
<tr>
<td></td>
<td>1.275</td>
<td>269.4</td>
<td>2.2</td>
<td>7.76</td>
</tr>
<tr>
<td>$^{54}\text{Mn}$</td>
<td>0.835</td>
<td>222.</td>
<td>21.</td>
<td>9.1</td>
</tr>
<tr>
<td>$^{60}\text{Co}$</td>
<td>1.173</td>
<td>267.</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1.332</td>
<td>270.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$^{133}\text{Ba}$</td>
<td>0.0308</td>
<td>6.2</td>
<td>4.</td>
<td>42.4</td>
</tr>
<tr>
<td></td>
<td>0.080</td>
<td>18.4</td>
<td>6.2</td>
<td>28.1</td>
</tr>
<tr>
<td></td>
<td>0.356</td>
<td>94.1</td>
<td>14.</td>
<td>14.3</td>
</tr>
<tr>
<td>$^{226}\text{Ra}$</td>
<td>0.088</td>
<td>16.1</td>
<td>6.6</td>
<td>27.2</td>
</tr>
<tr>
<td></td>
<td>0.352</td>
<td>95.</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0.609</td>
<td>162.2</td>
<td>19.</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td>1.12</td>
<td>266.</td>
<td>2.2</td>
<td>8.84</td>
</tr>
<tr>
<td></td>
<td>1.76</td>
<td>279.9</td>
<td>2.6</td>
<td>6.65</td>
</tr>
<tr>
<td></td>
<td>2.20</td>
<td>289.</td>
<td>3.2</td>
<td>6.55</td>
</tr>
<tr>
<td>$^{241}\text{Am}$</td>
<td>0.060</td>
<td>12.</td>
<td>5.1</td>
<td>30.8</td>
</tr>
<tr>
<td>$^{241}\text{Pu-Be}$</td>
<td>2.23</td>
<td>290.</td>
<td>3.2</td>
<td>6.46</td>
</tr>
<tr>
<td></td>
<td>4.43</td>
<td>339.1</td>
<td>4.5</td>
<td>4.57</td>
</tr>
</tbody>
</table>

*If a photopeak is not completely resolved from neighboring photopeaks, the peak width is not measured.
Figure 8

Energy calibration for the "A" analyzer. The points mark the photopeaks of the calibration sources. The "A" analyzer gain was determined to be

$$E(\text{keV}) = 14.6 + 3.61 N$$

where $N$ is the channel number and ranges from 1-256.
Figure 8

Energy Calibration

Energy [MeV]

Channel Number

0 32 64 96 128 160 192 224 256

0 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0

Figure 9

Energy calibration for the "B" analyzer. The points mark the photopeaks of the calibration sources. The "B" analyzer gain was determined to be

\[ E(\text{MeV}) = 0.685 + 0.045(N-256) \]

where \( N \) is the channel number and ranges from 257-512.
determining the quantity $\Delta E_{\text{FWHM}}$ from the photopaks of the sources listed in Table II, the resolution characteristics of both analyzers were computed. Log-log plots of the resolution versus energy showed a power law behavior of the following form:

\[ R(\%) = 8.81 \ E(\text{MeV})^{-0.458} \]

\[ R(\%) = 8.89 \ E(\text{MeV})^{-0.458} \]

The energy resolution for both analyzers was close to the $E^{-0.5}$ power law expected from purely statistical considerations.

C. FLIGHT HISTORY

Because the terrestrial atmosphere is opaque to gamma-rays, the observation of celestial gamma-ray sources makes it essential that the detector be lifted to altitudes of at least 120,000 ft. This corresponds to a residual atmospheric depth of less than 5 gm/cm$^2$. In the present experiment, the balloon-borne gamma-ray detector was launched at 2207 UT on 1974 April 2 from Rio Cuarto, Argentina. The balloon and payload were launched by personnel of the National Scientific Balloon Facility. The detector reached a float altitude of about 127,000 ft. approximately three hours after launch. This corresponds to an atmospheric depth of 4 gm/cm$^2$. The payload remained at depths that varied between 3.0 and 4.3 gm/cm$^2$ for the remainder of the flight.
The radiogalaxy Centaurus A was observed for approximately four hours (0059-0447 UT). The detector was then pointed at the discrete galactic X-ray source GX1+4. Observations of this source were made between 0507 to 1307 UT. During the observation of both sources a cyclic pattern of a 10 minute source observation followed by a 10 minute background was used. Twenty-three source segments were obtained in which GX1+4 was observed in addition to twenty-two background segments. The source GX1+4 was picked up as it was rising in the east at a zenith angle of about 55°. It was observed through transit to a zenith angle also of about 55° as it was setting in the west. Instead of rotating a full 180° in azimuth between source and background segments, the detector was driven only about 145°. Rather more serious problems involved a sticky hour angle drive in the early part of the flight. Compensation was arranged by sending intermittent "double-quick" RA drive commands. At 1310 UT, the 5-volt power supply failed, effectively terminating the experiment. Shortly thereafter the flight was terminated with the gondola and detector assembly impacting at Ortiz Basuldo, Argentina. Since the parachute-release command did not work on impact, the instrument was dragged some distance, resulting in structural damage. However, the detector assembly itself did not sustain any serious damage.
IV. DATA REDUCTION

The extraction of a corrected source spectrum from the analog flight tapes is a rather lengthy process. It involves a number of distinct computer programming steps. These are schematically represented in Figure 10. The data reduction process can be viewed as composed of three basic parts: an initial set of programs that reformat the time and the gamma-ray data; a SEGMENT program that accumulates an uncorrected spectrum for any designated time interval; and a final set of programs that yield a fully corrected residual source spectrum.

A. INITIAL PROGRAMS

The flight data including the gamma-ray count data, the corresponding arrival times for these events, and the housekeeping data were all recorded on 7-track analog tape, as noted earlier. To get the gamma-ray and time data into a more compact and useful format, an analog to digital (ATOD) conversion process was run on the SDS 92 A&B computers of the Space Physics and Astronomy Department. The analog flight tapes were played back in parallel with the Nuclear Data pulse-height analyzer. The ATOD program took the input data stream and wrote it on digital tape using a format with a fixed record length of 4092 words.
Figure 10

Block diagram of the complete data reduction and analysis procedures. The process begins with the digitization of the analog flight tapes recorded at the ground station and culminates with the computation of a fully corrected source spectrum.
Each analog tape was taken to define a single file on the digital tape. At the end of each analog tape (and digital file), the last record generally did not contain the full 4092 words; the record was completed with zeros by using a 100 kHz signal in place of the input data.

The second step in the initial sequence of programming involved the use of a CONVRT program which was also run on the SDS computers. The function of this program was to read the digital flight tape written by the ATOD program and convert the BCD time code to a 36 bit integer giving the time of each gamma-ray event in milliseconds. The result of this program was a second digital tape that preserved the file and record designations present on the first digital flight tape. Normally the time lag in milliseconds on each gamma-ray event progressively increases. However due to electronics problems, bad spots on the analog flight tapes, etc., errors in the time data occasionally occur. These errors may take several forms including time reversals and dropouts. In the former case, the time associated with a given gamma-ray event may be less than the time registered for the event just preceding it. In the latter case, entire blocks of time designation extending over tens to hundreds of milliseconds may be completely garbled.

To locate these time data errors on the CONVRT tape, a CONVRT READ program was run on the SDS 92A. This program searched every record of each file on the CONVRT tape for
time dropouts, reversals, etc. If the data within a given record were free of such dropouts or reversals, only the channel number and time corresponding to the first and last gamma-ray events within that record were printed. However, if a time error should occur within a record, the entire contents of that record are printed out, i.e., the channel number and arrival time in milliseconds for every gamma-ray event within that record. By looking through the CONVRT READ printout, the time of the last good event preceding a bad zone and the time of the first good event immediately following such a zone could be readily noted. A tabulation of these times for all the source and background segments obtained from 0507 to 1307 UT was made. These time data were transferred to cards which were later used to excise gamma-ray data within the "bad" zones from accumulation into a SEGMENT spectrum.

B. SEGMENT

This intermediate stage in the data reduction process has a two-fold task. First, the CONVRT tape must be segmented in time so as to accumulate an uncorrected spectrum for each of the source and background segments. A second application of this program is to segment the CONVRT tape in both time and channel number to obtain normalized counting rates for a given set of channel sums. A considerable amount of information can be obtained from an analysis of
the normalized count rates for the individual segments. First, an inspection of the data can provide a preliminary idea of the source spectrum. Secondly, the detector pointing during the background segments can be compared with the positions of known discrete sources. If any strong sources were within the field of view during a particular background segment, then this segment should display an enhanced count rate relative to the others. Finally, the spectral features present in the instrumental background can be readily identified if all of the background segment data is combined to yield a single 512 channel spectrum. Such spectral features can be utilized to make an in-flight energy calibration for the detector. A comparison of the combined source segment data with that of the background also provides information about the characteristics of the source spectrum.

Before segmenting the CONVRT tape into source and background segments, the beginning and end times of these segments had to be specified in milliseconds. During the ATOD process, the magnetometer housekeeping voltages were taken off the analog flight tapes and displayed on the housekeeping decommutator. With knowledge of the magnetometer calibrations, the south (source) and north (background) pointing segments were readily identified. Highly accurate time data were provided by the readout from a pair of time code generators, one of which looked at the time data on
the analog tape. The other generator was connected using a phase-locked loop circuit so that it was not affected by bad time data on the tape once proper synchronization had been established.

With knowledge of the begin and end times for each segment and the location (in time) of time reversals, drop-outs, etc., the EXPRESS SEGMENT L program was run on the SDS 92A. For each source and background segment the program accumulated a 512 channel pulse-height spectrum. All previously identified "bad" time intervals within each segment were ignored by the program.

1. NORMALIZED SEGMENT COUNT RATES

Before proceeding with the conversion of the uncorrected segment spectra into a final corrected residual spectrum, the SEGMENT program was utilized in preparing time history plots. Each such plot consists of the normalized counting rate in "Glenns" (counts/5 min.) over a fixed energy width for each of the source and background segments. In the "A" analyzer channel sums corresponding to a 1.5 FWHM energy width were computed. In the "B" analyzer channel sums representing 2.0 FWHM energy widths were taken. The generally much lower count rates in the "B" analyzer made it advisable to use a larger energy width than was employed in the "A". The begin and end channel numbers for each of these contiguous channel sums were determined from the
gain and energy resolution characteristics of the "A" and "B" analyzers. Representative time history plots are shown in Figures 11a,b and 12a,b for the "A" and "B" analyzers, respectively. An examination of these plots shows that the galactic center region is a relatively strong source of gamma-rays, especially at energies below about 600 keV. At the lowest energies the count rates display a rather clear time dependence. This is due to the fact that at these energies the cosmic gamma-ray background is a large fraction of the experimental background. Therefore this fraction will be maximized when the detector is at small zenith angles, as it was during the meridian transit of GX1+4.

2. BACKGROUND SEGMENT POINTING

To determine if known discrete X-ray sources were within the instrument's field of view during the various background segments, the pointing of the detector was computed for these various time intervals. The result is shown in Figure 13, where the pointing of the background segments has been plotted in galactic coordinates along with the positions of discrete X-ray sources as listed in the third Uhuru catalog. The time history plots (Figures 11a,b and 12a,b) were re-examined with reference to Figure 13. It was found that background segment 6 was taken when the radiogalaxy Cen A was at the edge of the
Figures 11a,b

Uncorrected count rates below 1.0 MeV measured as a function of local time. The error bars shown are plus and minus one standard deviation and are purely statistical in nature. The energy widths for which normalized counting rates were computed are all 1.5 FWHM.
Figure 11b
Figures 12a,b

Uncorrected count rates above 1.0 MeV measured as a function of local time. The error bars shown are plus and minus one standard deviation and are purely statistical in nature. The energy widths for which normalized counting rates were computed are all 2.0 FWHM.
Figure 12a
Figure 12b
Figure 13

Map of the celestial sphere in galactic coordinates showing the positions of discrete X-ray sources listed in the third Uhuru catalog. The short, heavy line segments depict the centers of the 13° wide regions from which the background was sequentially measured.
field of view. This segment displayed a statistically significant enhanced counting rate at energies below 200 keV compared to the other background segments. Data taken during the early part of the 1974-1 flight has established that Cen A is a rather intense source of low-energy gamma radiation (Hall et al. 1975). Background segments 10, 11, and 12, which were taken when the galactic plane was within the field of view, were also found to display enhanced counting rates at low energy. Background segment 10 was especially intense at low energies, giving counting rates comparable to "source" segments.

3. TOTAL SOURCE AND BACKGROUND COUNT RATE

In addition to the preparation of the time history plots, it was also deemed desirable to prepare plots of total source and background counting rate as a function of channel number. These plots are depicted in Figure 14 and 15 for the "A" and "B" analyzers, respectively. The following prescription for the total uncorrected count rate $R_i$ in the $i$th channel was used:

$$R_i = \left( \sum_{j=1}^{N} \frac{X_{ij}}{\sigma_{ij}^2} \right) \left( \sum_{j=1}^{N} \frac{1}{\sigma_{ij}^2} \right)^{-1}$$

where the subscript $j$ refers to the segment number and $\sigma_{ij}$ is the standard deviation corresponding to count rate $X_{ij}$. The data from the twenty-three source segments (219
Figure 14

Total uncorrected source and background count rates as a function of pulse-height for energies below 1.0 MeV. The background features near ~200 keV and 490 keV are due to activation of NaI.
Figure 15

Total uncorrected source and background count rates as a function of pulse height for energies greater than 1.0 MeV.
minutes of data) were used to compute the total uncorrected "source" count rate as a function of channel number. The corresponding total "background" count rate was found by using the data from all twenty-two background segments (217 minutes of data). The differences between the "source" and "background" count rate at a given channel number is a measure of the source strength. However, it should be emphasized that these data are not corrected for either the continuously varying zenith angle of the source or for the detector efficiency.

A number of interesting features are evident in these two plots. In Figure 14, a pronounced peak is present in the background near channel 50; this corresponds to an energy of about 200 keV. Also present in the background is a very broad spectral feature extending approximately from channel 110 to 150. Its rather poorly defined mean energy is at about 490 keV. Inspection of Figure 14 also shows that a net count rate from the source is easily discernible, especially for channels below 150 (i.e. for energies less than 550 keV). The enhancement in the source count rate around channel 136 is particularly of interest since it is within several keV of the positron annihilation energy at 0.511 MeV. Examination of Figure 15 reveals that a small excess due to the source is present in about the first thirty channels
in the "B" analyzer. Channel 287 is at an energy of about 2.0 MeV. A rather prominent enhancement in the source count rate is also present near channel 340 (i.e. an energy of approximately 4.5 MeV).

C. FINAL DATA REDUCTION PROCEDURES

The final stage of the data reduction process involves the combination of the source and background segments to form partial residuals which are then combined with appropriate correction factors to yield a final, fully corrected residual source spectrum. This spectrum, which is in terms of counts/5 min as a function of channel number, is then converted to flux units of photons/cm²-sec-keV. Channel sums are then computed and a power law or exponential fit where appropriate.

1. BACKGROUND SUBTRACTION

The first step is to compute a set of single channel "partial residuals", the number of which is equal to the number of source segments. A partial residual is computed by obtaining a weighted average of the background segments adjacent to a source segment on a channel-by-channel basis. This average background is then subtracted from the source segment also on a channel-by-channel basis.

The prescription for computing the mean background count rate $\overline{B}_{ij}$ and its associated standard deviation $\sigma_{ij}$ is the following:
\[ B_{ij} = \left\{ \frac{B_{ij-1}}{(\sigma_{ij-1}^B)^2} + \frac{B_{ij+1}}{(\sigma_{ij-1}^B)^2} \right\} \left[ \frac{1}{(\sigma_{ij-1}^B)^2} + \frac{1}{(\sigma_{ij+1}^B)^2} \right]^{-1} \]

\[ \sigma_{ij}^B = \left[ \frac{1}{(\sigma_{ij-1}^B)^2} + \frac{1}{(\sigma_{ij+1}^B)^2} \right]^{-1/2} \]

The quantity \( P_{ij} \) and its standard deviation \( \sigma_{ij} \) are then computed as follows:

\[ P_{ij} = S_{ij} - \bar{B}_{ij} \]

\[ \sigma_{ij} = \left[ \left( \sigma_{ij}^S \right)^2 + \left( \sigma_{ij}^B \right)^2 \right]^{1/2} \]

where \( X_{ij} \) is just the \( i \)th channel count rate in the \( j \)th source segment and \( \bar{B}_{ij} \) is the mean \( i \)th channel count rate in the \( j-1 \) and \( j+1 \) background segments.

The above procedure was used for all source segments which were bracketed by background segments. However, no background segment preceded the first source segment and no background followed the last source segment. To compute the first and last partial residuals, the following was done:

\[ P_{ij} = S_{ij} - B_{ij} \]

\[ B_{ij} \equiv B_{ij+1} \text{ for } j=1 \]

\[ B_{ij} \equiv B_{ij-1} \text{ for } j=23 \]

\[ \sigma_{ij} = \left[ \left( \sigma_{ij}^S \right)^2 + \left( \sigma_{ij}^B \right)^2 \right]^{1/2} \]

\[ \sigma_{ij}^B \equiv \sigma_{ij+1}^B \text{ for } j=1 \]

\[ \sigma_{ij}^B \equiv \sigma_{ij-1}^B \text{ for } j=23 \]
It should be noted that it is desirable to have all the source segments bracketed by backgrounds. This permits the computation of accurate background count rates for the time intervals during which the "source" observations were conducted. If only one background segment, and not the mean of two such segments, is used in the subtraction, zenith angle and time-dependent effects are introduced into the resultant partial residual. However, this effect is small due to the short time duration of the individual source and background segments. Since the source spectrum is computed from a weighted average of all twenty-three partial residuals, the effect of small distortions present in only two of these will be negligible.

2. ATMOSPHERIC ABSORPTION

Before these partial residuals can be combined further, atmospheric absorption of gamma-rays reaching the detector from the celestial source must be corrected for. Each source segment represents a different path length through the atmosphere for gamma-rays originating in the celestial source. To correct for this atmospheric attenuation, the correction factor must include an energy-dependent cross-section for the absorption of gamma-rays in air and a specification of the effective atmospheric depth. A correction factor of the following form was used:
\[ A_{ij} = \exp[\theta_i P_j \sec(ZA_j)] \]

where \( \theta_i \) is an energy-dependent attenuation coefficient in \( \text{cm}^2/\text{gm} \), \( P_j \) is the atmospheric pressure in millibars, and \( ZA \) is the zenith angle. Using the convention previously adopted, the subscript \( i \) denotes the energy of the \( i \)th channel while \( j \) refers to the source segment number. The values of \( \theta \) are tabulated in Table III and were taken from a chart prepared from the 39th edition of the Handbook of Chemistry and Physics and NBS Report No. 1003 (1952) as reproduced in the Radiological Health Handbook. The mean value of \( P \) was determined for each source segment from the altimeter data. This was done simply by computing the mean value of the altitude for each source segment and converting this to a pressure in millibars using tables in the U.S. Standard Atmosphere (1962). Finally, the zenith angle was computed at a time corresponding to the mid-point of each source segment. Designating the atmospheric correction factor for the \( i \)th channel of the \( j \)th partial residual as \( A_{ij} \), it follows that:

\[ P_{ij}^* = P_{ij} A_{ij} \]

\[ \sigma_{ij}^* = \sigma_{ij} A_{ij} \]
Table III.

Gamma-ray attenuation coefficients in air in cm$^2$/gm. These energy-dependent coefficients were used to correct for atmospheric attenuation in the source segments.
TABLE III.

Gamma-Ray Attenuation Coefficients In Air

<table>
<thead>
<tr>
<th>$E_Y$ (MeV)</th>
<th>$\theta$ (cm$^2$/gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.030</td>
<td>0.310</td>
</tr>
<tr>
<td>0.040</td>
<td>0.220</td>
</tr>
<tr>
<td>0.050</td>
<td>0.190</td>
</tr>
<tr>
<td>0.060</td>
<td>0.180</td>
</tr>
<tr>
<td>0.070</td>
<td>0.170</td>
</tr>
<tr>
<td>0.080</td>
<td>0.160</td>
</tr>
<tr>
<td>0.090</td>
<td>0.150</td>
</tr>
<tr>
<td>0.100</td>
<td>0.145</td>
</tr>
<tr>
<td>0.200</td>
<td>0.120</td>
</tr>
<tr>
<td>0.300</td>
<td>0.100</td>
</tr>
<tr>
<td>0.400</td>
<td>0.095</td>
</tr>
<tr>
<td>0.500</td>
<td>0.090</td>
</tr>
<tr>
<td>0.600</td>
<td>0.080</td>
</tr>
<tr>
<td>0.700</td>
<td>0.075</td>
</tr>
<tr>
<td>0.800</td>
<td>0.070</td>
</tr>
<tr>
<td>0.900</td>
<td>0.067</td>
</tr>
<tr>
<td>1.000</td>
<td>0.064</td>
</tr>
<tr>
<td>2.000</td>
<td>0.045</td>
</tr>
<tr>
<td>3.000</td>
<td>0.036</td>
</tr>
<tr>
<td>4.000</td>
<td>0.030</td>
</tr>
<tr>
<td>5.000</td>
<td>0.027</td>
</tr>
<tr>
<td>$E_Y$ (MeV)</td>
<td>$\theta$ (cm$^2$/gm)</td>
</tr>
<tr>
<td>------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>6.000</td>
<td>0.025</td>
</tr>
<tr>
<td>7.000</td>
<td>0.023</td>
</tr>
<tr>
<td>8.000</td>
<td>0.022</td>
</tr>
<tr>
<td>9.000</td>
<td>0.021</td>
</tr>
<tr>
<td>10.000</td>
<td>0.020</td>
</tr>
</tbody>
</table>
where * implies correction for atmospheric attenuation. It should be noted that the value of $A_{ij}$ appropriate to each channel was obtained by interpolating in the table of $\Theta$ values and then computing the exponential. A modified Lagrange interpolation subprogram accurate to better than 5 parts in 1000 was utilized for the interpolation.

3. PARTIAL RESIDUAL COMBINATION

The partial residuals, corrected for atmospheric absorption, were combined using a weighted averaging subroutine. The following prescription was used:

$$R_i = \left[ \frac{N}{\sum_{j=1}^{N} \frac{P^{*}_{ij}}{\sigma_{ij}^2}} \right] \left[ \frac{N}{\sum_{j=1}^{N} \frac{1}{\sigma_{ij}^2}} \right]^{-1}$$

$$\sigma_i = \left[ \frac{N}{\sum_{j=1}^{N} \frac{1}{\sigma_{ij}^2}} \right]^{-1/2}$$

where $R_i$ is the partially corrected residual count rate in the $i$th channel and $\sigma_i$ is the corresponding standard deviation. Twenty-three partial residuals were combined to yield the final source spectrum.

4. INSTRUMENTAL CORRECTIONS

To obtain a fully corrected source spectrum it is necessary to next build in the energy-dependent correction factors that compensate for instrumental absorption, intrinsic efficiency, and K X-ray escape from the central detector.
crystal. Because of the considerable importance of these correction factors, each of them will be discussed in some detail.

a) INSTRUMENTAL ABSORPTION

The instrumental absorption, especially important at low energies, was determined experimentally. As shown in Figure 16, the detector was oriented with the gamma-ray axis perpendicular to the face of a wall some 20 ft. distant. A second smaller NaI crystal with attached phototube was mounted directly under the main detector housing and parallel to the axis of the larger instrument. A gamma-ray source was counted at position #1 for the large detector and at position #2 for the smaller unit. This was done to correct for parallax effects. Photopeaks of roughly gaussian shape were obtained from both detectors. Under the assumption of a gaussian distribution, a width corresponding to one-half the maximum peak counting rate value was taken and all counts summed within this energy interval. The only absorption effects in the small detector were known to be caused by an aluminum plate of 1/16" thickness and a layer of MgO of 0.67 gm/cm² which served as a reflector. The counting rates of the small crystal were corrected for these absorption effects. Then by allowing for the difference in area of the two crystals and the difference in spectra accumulation times, counting rates that were
Figure 16

Orientation of the gamma-ray telescope for instrumental absorption measurements. A 3" dia. NaI detector, whose absorption characteristics were known, was mounted parallel to the axis of the larger instrument. Various radioactive sources were counted at positions #1 and #2 for the large and small detectors, respectively.
DETECTOR ORIENTATION FOR INSTRUMENTAL ABSORPTION MEASUREMENTS

Figure 16

LARGE DETECTOR

#1

SMALL DETECTOR

#2
directly comparable were obtained. Since the percentage 
transmission of the smaller crystal was measured at a number 
of different energies, the transmission characteristics of 
the larger instrument could then be computed at these same 
energies. From a log-log plot of the percent transmission 
as a function of incident gamma-ray energy, it followed 
that a power law relationship existed up to an energy of 
approximately 680 keV. Accordingly a power law of the 
form

\[ T(\%) = 1.095E^{0.20}(\text{keV}) \]

was fit to the data. The reciprocal of T was taken as the 
correction factor. A plot of this correction factor as 
a function of energy is shown in Figure 17. For energies 
above \(\sim\) 680 keV, the instrumental absorption was negligible 
and no correction was therefore made.

b) INTRINSIC EFFICIENCY

Correction factors for the intrinsic efficiency of the 
central detector crystal were computed from results reported 
by Miller et al. (1957). These results were obtained through 
the use of a Monte Carlo program to simulate gamma-ray histories 
within crystals of NaI having various dimensions. A large number "N" of photon histories was sampled (5000 in 
this case) and the number of events "I" in which a primary 
gamma-ray photon interacts at least once within the crystal
Figure 17

Instrumental correction factors as a function of gamma-ray energy. The total correction factor is shown together with those for K X-ray escape, instrumental absorption, and photopeak (intrinsic) efficiency.
Figure 17

CORRECTION FACTOR

TOTAL CORRECTION

INSTRUMENTAL ABSORPTION

K X-RAY ESCAPE

PHOTOPEAK EFFICIENCY

ENERGY (MeV)
was recorded. Also counted was the number of photon histories "A" for which both the primary and secondary photons were absorbed within the crystal. The efficiency is then given by A/I. The results published by Miller et al. (1957) included efficiencies and photofractions for NaI crystals 4" and 8" in diameter and 2" thick at five different energies. The correction factor desired is the intrinsic efficiency given by A/N. The values of A/N as a function of energy were plotted for the two different sized crystals and smooth curves drawn through the points. A curve for the central detector crystal which has a 6" diameter and 2" thickness was then interpolated for graphically. From this curve the correction factor values at a number of different energies were tabulated. The resultant correction factor array was referenced by the interpolating subprogram to determine the appropriate single-channel correction factors. A plot of the intrinsic efficiency correction factor as a function of energy is shown in Figure 17.

The efficiency calculations described above have recently been compared with the results of a MonteCarlo computer code (Steyn et al. 1973). Because of the code's flexibility it was possible to accurately mock-up the geometry of the present Rice detector together with the anticoincidence system. Comparing these computations with those of Miller et al. (1957) showed agreement to within 10%.
It should be noted that the utilization of an efficiency correction factor (as was done in the present experiment) assumes that all Compton-scattered photons that escape the central detector are vetoed by the anticoincidence system. The validity of this assumption may be tested by examining the response of the instrument to a calibration source. The instrumental response to a $^{22}$Na source is shown in Figure 18. Compton-scattered photons that escape through the guard show up as a "tail" at energies below the photopeak produced by the source. It was found that for a $^{22}$Na source, the count rate in the Compton tail was less than 11% of the counting rate in the photopeak. It therefore follows that the contribution at any energy from photons scattered down from higher energies will be small if the gamma-ray flux decreases rapidly with increasing energy. Since the fluxes of virtually all celestial gamma-ray sources decrease rapidly with increasing energy, the error introduced by using an efficiency correction will be small compared with the statistical errors. Consequently, an elaborate matrix inversion process is not necessary.

c) K X-RAY ESCAPE

At low energies (32 keV-100 keV) the effect of K X-rays escaping from the central detector crystal must be considered. To determine the appropriate correction factors, the article on "The Scintillation Method" by Neiler and Bell in
Figure 18

The instrumental response to a $^{22}_{\text{Na}}$ calibration source. The counting rate per channel in the Compton tail is less than 11% of that in the peak at 511 KeV.
K. Seigbahn's Alpha-, Beta-, and Gamma-Ray Spectroscopy (Vol. I) was referenced. Specifically, a plot of the quantity Q versus incident gamma-ray energy was used where Q is defined to be the ratio of the number of X-rays that leave the crystal to the number of gamma-rays that enter it. This plot was digitized to give the correction factor as a function of energy. Interpolation within the resultant correction factor array was performed to yield the correction factor appropriate to each channel. A plot of this correction factor as a function of energy is shown in Figure 17.

5. CORRECTED SPECTRUM

With the inclusion of all these correction factors, a final, fully corrected spectrum for the 13° diameter region of sky centered on GX1+4 was obtained. The prescription for the correction of the residual count rates and corresponding standard deviations is as follows:

\[ R_i^t = R_i T_i Y_i Z_i \]

\[ \sigma_i^t = \sigma_i T_i Y_i Z_i \]

where \( T_i \), \( Y_i \), and \( Z_i \) are the ith channel correction factors for instrumental absorption, intrinsic efficiency, and K X-ray escape, respectively. The count rates were then converted to flux units of photons/cm²-sec-keV. To improve the statistics relative to the single channel fluxes, sets
of contiguous channel sums were computed. For channels in the "A" analyzer, sums corresponding to widths of 0.5 FWHM, 1.0 FWHM, 1.5 FWHM, and 2.0 FWHM were computed. In the "B" analyzer the summing interval corresponded to 1.0 FWHM, 2.0 FWHM, and 4.0 FWHM resolution widths. For a given width such as 1.0 FWHM, the beginning and end channel numbers for a set of contiguous channel sums spanning the two analyzers were computed by an iterative procedure. The results of this analysis will be discussed in the next section.
V. RESULTS AND THEIR SIGNIFICANCE

Examination of the gamma-ray spectrum for the galactic center region revealed the presence of a power law continuum together with several gamma-ray lines superimposed. One of the lines is evidently due to the annihilation of positrons while the others are nuclear in origin.

A. CONTINUUM

The spectrum of the galactic center region as determined by the data reduction process is depicted in Figure 19. If a power law fit is made to all channel sums between 0.040-2.0 MeV the following power law is obtained:

\[ F(\text{Photons/cm}^2\text{-sec-keV}) = (8.9 \pm 1.3)E^{-2.43 \pm 0.03}(\text{keV}) \]

This expression produces a minimum in the value of $\chi^2$ but gives a reduced value of $\chi^2$ of 5.08 for 32 degrees of freedom. Large contributions to this value result from flux values near 0.5 MeV and also from the energy interval between 1.2-2.0 MeV. A somewhat smaller contribution is made by the flux around 0.9 MeV. The presence of these line-like features thus implies that the power law fit to the continuum should exclude the corresponding energy intervals. A power law fit to the data was made in the energy interval from 0.05 MeV to 0.80 MeV excluding a 2.0 FWHM energy band.
Figure 19

Measured differential energy spectrum of the 13° region of sky centered on GX1+4. The solid line is the best fit power law to the data. Flux sums are 0.5 FWHM below 1.0 MeV and 4.0 FWHM above 1.0 MeV.
around 0.5 MeV. The result was the following:

$$ F(\text{photons/cm}^2\text{-sec-keV}) = (40.7 \pm 12.5) E^{-2.78 \pm 0.06} \text{(keV)} $$

This fit gave a reduced $\chi^2$ value of 0.932 for 19 degrees of freedom. There is a 54% probability that random fluctuations will produce $\chi^2$ values greater than 0.932. The quoted errors are purely statistical in nature, being those that increment $\chi^2$ by unity. If the source of the continuum radiation is assumed to be the galactic center distance, i.e. 10 kpc, then the source luminosity is $6.5 \times 10^{37}$ ergs/sec.

There is no evidence for a detectable flux above 12.27 MeV from the galactic center region. The overflow counting rate difference (for events with energy greater than 12.27 MeV) was found to be $(1.25 \pm 1.34)$ counts per five minutes. This is as compared to a background overflow count rate of 30 counts per five minutes.

The above power law fit to the data is in reasonable agreement with observations of GX1+4 at lower energies. During 1970, October 15-16, Lewin et al. (1971) observed GX1+4 in the 20-100 keV energy range. It was found that the data could be fit by either an exponential with $kT = 28 \pm 12$ keV or a power law with index $\alpha = 2.4 \pm 0.7$. On 1972 April 5 Ricker et al. (1974) observed GX1+4 over the 17-115 keV energy interval. Owing to the limited energy range over which data was accumulated, both an exponential energy spectrum with $kT = 18 \pm 2$ keV and a power law with spectral
index \( \alpha = 2.6 \pm 0.2 \) were found to give acceptable fits to the data. The spectral index obtained by the present experiment is thus within the uncertainty in the spectral indices reported by previous observers.

There is some evidence that the X-ray and low energy gamma radiation from GX1+4 is pulsed. Lewin et al. (1971) found a 2.3 minute periodicity in the data but this was not detected by Ricker et al. (1974) during their 1972 flight. The data from the present experiment has not yet been analyzed from the reported 2.3 minute periodicity.

It should be noted that the above results were obtained using all of the source and background data. However, as has been noted previously, some of the background segments displayed enhanced counting rates, especially at low energy. Accordingly, a spectrum was computed in which background segments 5, 6, 10, 11 and 12 were deleted along with the bracketed source segments (6, 10, 11, and 12). The resultant spectrum is shown in Figure 20. A power law was fit to the data in the energy interval extending from 0.05 to 0.80 MeV and excluding a 2.0 FWHM energy band around 0.5 MeV. The following expression was obtained:

\[
F(\text{photons/cm}^2\text{-sec-keV}) = (98.1 \pm 45.3)E^{-2.90 \pm 0.08}(\text{keV})
\]

This particular fit gave a reduced \( \chi^2 \) value of 0.679 for 12 degrees of freedom. As one would expect the continuum is steeper than that obtained when the suspect background data
Figure 20

Measured differential energy spectrum of the 13° region centered on GX1+4 but with the segments taken around transit deleted. The solid line is the best fit power law to the data.
GALACTIC CENTER REGION
1974 APRIL 2
Φ 1.0 FWHM
+ TRANSIT SEGMENTS DELETED

(98.10 ± 45.38) E^{-2.90 ± 0.08}

Figure 20
is retained. However, because of the reduced amount of source data used in the generation of the above spectrum, the statistical confidence associated with various spectral features is less than when all the data are used. Accordingly, it was decided to accept a small possible error in the power law index and utilize the spectrum which resulted from the retention of all of the source and background data.

It might be expected that the source segments bracketed by the suspect backgrounds could be retained if the backgrounds were replaced by ones taken at different galactic latitude. This approach was followed and a residual spectrum computed. A power law fit to the data excluding a 2.0 FWHM width about 0.5 MeV gave a reduced $x^2$ of 5.77 for 13 degrees of freedom. The poorness of the fit is due to the coupling of zenith-angle and time-dependent effects present in the background data into the residual spectrum. Accordingly, no further efforts were made in this direction. For such an approach to be successful the suspect background segment data must be replaced with synthetic backgrounds. Such backgrounds could be computed given the spectral dependence of the zenith angle and time-dependent effects.

The small difference in the power law index (0.12) in the fits to the continuum (depending on whether or not certain segments are retained) should not be considered significant. The reason is that the measured continuum is very likely due to the contributions of a number of sources and not to a
single discrete source. As shown in Figure 13, a number of known discrete X-ray sources were within the detector's field of view during the observation of GX1+4. The relative strengths of these sources at gamma-ray energies is uncertain. Both the present detector and others previously flown (Johnson and Haymes, 1973) are unable to resolve such closely spaced sources. Clearly if it were known that a single discrete source was responsible for the continuum emission, the deletion of the suspect background segments and bracketed source segments would be completely justified.

The mechanism responsible for the production of the continuum radiation is uncertain. Both the synchrotron and inverse-Compton processes yield power law spectra. Under certain conditions thermal bremsstrahlung can also produce a power law-like spectrum. To determine the particular mechanism responsible for the continuum emission, it is necessary to develop a self-consistent model of the source region. Such a model should utilize the available infrared, radio, X-ray and gamma-ray data. To date such a model has not been developed for GX1+4, although Grindlay (1974) successfully developed such a model to explain the emission from the nucleus of NGC 5128.

B. GAMMA-RAY LINES

1. 0.5 MEV FEATURE

The spectrum below 1.0 MeV is shown in Figure 21. Present at approximately 0.5 MeV is a feature that lies 3.5σ above
Figure 21

Measured differential energy spectrum of the galactic center region for energies less than 1.0 MeV. The flux sums plotted are each 0.5 FWHM wide in energy. The best fit power law and the gaussian fit to the spectral feature at 522 ± 11 keV are also shown.
the continuum. A gaussian fit to the feature gave an average energy of 522±11 keV. However, because the peak counting rate occurs at 505 keV and the statistics have evidently made the line profile asymmetric, the feature is most probably the 511 keV line characteristic of positron annihilation. The line flux was computed to be \((8.0±2.3) \times 10^{-4}\) photons/cm\(^2\)-sec. Due to the somewhat asymmetric profile of the line, its true width is especially subject to error. A gaussian fit to the line with the width as a free parameter gave a broadening of 10%.

The results of the present experiment comprise the third report of a spectral feature near 0.5 MeV in the gamma radiation from the galactic center region. The combined data from the two previous observations gave a flux of \((1.8±0.5) \times 10^{-3}\) photons/cm\(^2\)-sec at an average energy of 476±12 keV (Johnson and Haymes, 1973). The gaussian fit to this feature, superimposed on the fitted power law, is shown in Figure 22. It should be emphasized that the data represented by Figure 22 was obtained from the observation of the sources GX5-1 and GX3+1 during the 1970-4 and 1971-2 flights, respectively.

The difference in the mean energy of the spectral feature observed in the present experiment and that obtained in the two preceding flights is thus at the 2.8σ level. This difference is real and cannot be attributed to a calibration error. The correctness of this assertion can be established
Figure 22

The measured flux from the galactic center region as determined by a weighted average of the 1970 and 1971 observations. The pulse-height channels have been combined into consecutive 30 keV energy intervals. Also shown is the best fit power law with the fitted gaussian photopeak superimposed at an energy of 476 keV.
by a comparison of the uncorrected source and background count rates obtained from the 71-2 and 74-1 flights. These are shown in Figures 23 and 14, respectively. In the instrumental background of both flights a broad feature was present with a peak at around 490 keV. In the 71-2 flight the excess of the source over the background was on the low-energy side of this feature while in the 74-1 flight the excess was on the high-energy side. It would thus appear that two different spectral features have been observed, one on each side of 0.5 MeV.

As noted previously, three of the background segments (10, 11, and 12) were taken in the galactic plane. These segments were treated as "sources", while background segments taken at higher galactic latitudes were used as "backgrounds." A residual spectrum was computed which was characterized by the following power law:

\[ F(\text{photons/cm}^2\text{-sec-keV}) = (5.2 \pm 2.9)E^{-2.40 \pm 0.1} \text{(keV)} \]

This spectrum is depicted in Figure 24. An excess above the power law was found to be present in a 1.5 FWHM energy interval centered on 470 keV. Taking 0.5 FWHM sums in this interval gave a peak flux of \( 2.26 \times 10^{-5} \) photons/cm\(^2\)-sec-keV between 454 keV and 487 keV. This constitutes a 2.0σ excess over the power law. A fit of the form

\[ F = AE^{-\gamma} + B_1 \exp[-(E-E_1)^2/2\delta_1^2] + B_2 \exp[-(E-E_2)^2/2\delta_2^2] \]
Figure 23

Uncorrected total source and background count rates as a function of pulse-height for the 1971 flight.
Figure 24

The measured differential spectrum for the galactic plane obtained by treating three backgrounds as "source" segments. The best fit power law to the data is also shown.
Figure 24
was made to the spectrum over the 380 to 570 keV energy interval using channel sums 0.2 FWHM wide. The energies $E_1$ and $E_2$ were fixed at 431 keV and 478 keV, respectively. The gaussian widths $\delta_1$ and $\delta_2$ were also held constant at values corresponding to the instrumental energy resolution (FWHM), $\Delta E$, at the two line energies. The relation between $\delta$ and $\Delta E$ is the following:

$$\Delta E = [8 \ln(2)]^{1/2}\delta$$

The fit yielded a reduced $\chi^2$ value of 1.365 for 33 degrees of freedom. The intensities at 431 keV and 478 keV were found to be $(8.3\pm8.7) \times 10^{-5}$ and $(7.4\pm9.2) \times 10^{-5}$, respectively, where the fluxes are in units of photons/cm$^2$-sec-keV. This fit is shown in Figure 25 together with the 0.5 FWHM flux sums for energies below 1.0 MeV. It should be noted that the above results are based on only about 30 minutes of "source" data. This accounts, in part, for the large uncertainty associated with the intensities at 431 keV and 478 keV, as computed by the fitting program.

A hypothesis capable of explaining the observational data must account for the two different spectral features which are present in the low-energy gamma-ray spectrum of the galactic center region. The feature with a mean energy of $\sim 470$ keV can be plausibly attributed to deexcitation gamma-rays from $^7$Be$^*$ and $^7$Li$^*$ at 431 keV and 478 keV, respectively.
Figure 25

Measured differential spectrum of the galactic plane below 1.0 MeV. Flux sums shown are 0.5 FWHM wide in energy. The best fit power law to the data is shown in addition to the gaussian fit to the spectral feature at 470 keV.
Two mechanisms for the production of the $^7\text{Be}^*$ and $^7\text{Li}^*$ nuclei have been proposed; one involves inelastic scattering and the other direct production of these nuclei in the first excited state by $\alpha\alpha$ reactions.

Inelastic scattering has the largest cross-section of the various gamma-ray producing nuclear interactions that result from the collision of cosmic rays with the interstellar medium. It is noteworthy that $^7\text{Li}$ has an anomalously high cosmic ray abundance due to its spallogenic formation (Reeves et al., 1970). In the interaction of $^7\text{Li}$ nuclei with the interstellar medium, the following two reactions are of particular importance:

- $^7\text{Li}(p,p')^7\text{Li}^*$; can emit a 478 keV gamma-ray
- $^7\text{Li}(p,n)^7\text{Be}^*$; can emit a 432 keV gamma-ray

The cross-section for the first of these reactions rises sharply around 1 MeV to a maximum between 3-4 MeV and then declines rapidly for energies near 10 MeV. The cross-section for the second of these two reactions is about one-third that of the first one over the 2-50 MeV energy range.

A second possible mechanism for the production of $^7\text{Be}^*$ and $^7\text{Li}^*$ nuclei has been advanced by Kozlovsky and Ramaty (1974). The following reactions are of interest:

- $^4\text{He}(\alpha,p)^7\text{Li}^*$
- $^4\text{He}(\alpha,n)^7\text{Be}^*$
where the two different nuclei are produced directly in the first excited state. The threshold and cross-section for the first of these reactions are about the same as for the production of $^7\text{Li}$ in the ground state. This implies a threshold energy of about 8.5 MeV per nucleon and a maximum cross-section of 100 mb near 10 MeV per nucleon. No data is presently available on the production of $^7\text{Be}^*$ in the first excited state. If these two nuclei are produced mainly by $\alpha$ particles with 10 MeV per nucleon, then the Doppler width of the de-excitation gamma-ray lines should be $\sim$30 KeV.

The relatively high abundance of $\alpha$ particles in cosmic rays and the interstellar medium tends to imply that the broadened lines at 431 keV and 478 keV should have intensities comparable to that expected for 511 keV radiation (Kozlovsky and Ramaty. 1974).

To determine whether inelastic scattering of $^7\text{Li}$ or $\alpha\alpha$ reactions are responsible for the observed radiation around 470 keV requires a careful evaluation of the available data. The importance of the inelastic scattering of $^7\text{Li}$ in accounting for the spectral feature at 473 keV (Johnson et al. 1972) has been emphasized by Fishman and Clayton (1972). In fitting the data from the 1970-4 flight, a model consisting of two gaussians superimposed on a power law was used. The mean energies of the gaussians were fixed at 432 keV and 478 keV while the energy widths were taken to be specified by the instrumental resolution ($\Delta E_{\text{FWHM}}$) at these two energies.
A good fit was obtained if the intensities of the 432 keV and 478 keV components are in the ratio of 1 to 3. As noted previously, a similar fit was made to the feature near 470 keV that resulted from treating three galactic plane backgrounds as sources. The intensities for the two components were found to be comparable. However, the uncertainties in the two intensities are so large that a 1 to 3 ratio could also be considered consistent with the data. It should be emphasized that neither the results obtained by Johnson et al. (1972) nor those from the present experiment are of sufficiently high resolution or statistical confidence to establish the presence of lines at both 432 keV and 478 keV. The available data therefore do not permit one to determine the relative importance of the inelastic scattering of \(^7\)Li and \(\alpha\alpha\) reactions in the production of low-energy gamma-rays at these two energies.

Although a unique determination of the nuclides responsible for the 470 keV radiation is not possible, the available data can still provide information on the spatial origin of this radiation. Table IV summarizes the relevant data from the various flights. There is evidently a correlation with the intensity of the 470 keV radiation and galactic longitude. This in turn suggests that a structural feature of the inner galaxy, the 4 kpc ring, is involved. The orientation of this structure in galactic longitude is depicted in Figure 26.
Table IV.

Listing of galactic longitude intervals for each of the observations in which a spectral feature near 500 keV was noted.
### TABLE IV.

SPECTRAL FEATURES NEAR 500 keV

<table>
<thead>
<tr>
<th>Flight</th>
<th>Galactic Longitude Interval</th>
<th>Mean Energy of Spectral Feature (keV)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>70-4</td>
<td>354°-17°</td>
<td>473</td>
</tr>
<tr>
<td>71-2</td>
<td>351°-15°</td>
<td>485</td>
</tr>
<tr>
<td>74-1</td>
<td>353°-8°</td>
<td>522</td>
</tr>
<tr>
<td>74-1</td>
<td>339°-392°</td>
<td>470</td>
</tr>
</tbody>
</table>

*The mean energy as determined by the fit of a single gaussian plus power law to the spectral feature. A fit to the combined 1970-4 and 1971-2 flight data gave a mean energy of 476 keV.
Figure 26

Orientation of the 4 kpc ring structure in galactic longitude. Enhanced radiation at 470 keV is present for directions taken along either side of this structure as seen from the earth.
It is interesting to note that the origin of this feature is uncertain. It has been suggested that it is a dispersion ring. Theoretical reasons for expecting a dispersion ring at the inner Lindblad resonance of the spiral pattern have been advanced by Contopoulos (1971) and Vandervoort (1973), among others. The 70 km/sec expansion velocity that is associated with the 4 kpc ring has led to speculation that it is the result of an explosion. Simonson (1973) constructed computer models for the region between 1 and 5 kpc using the available 21 cm data. He found that it could be described to a first approximation by a uniform disk in pure differential rotation.

Regardless of the detailed nature of the 4 kpc ring, there seems to be a correlation between the intensity of the 470 keV radiation and the column density of ring matter. Examination of Table IV indicates that the 470 keV flux originates primarily in the following two intervals in galactic longitude: 339° to 352° and 8° to 17°. As Figure 26 shows, these two intervals include directions along one or the other side of the 4 kpc ring as seen from the earth. If this simple model is correct, then the 470 keV flux should be at a minimum for intermediate values of galactic longitude where the column density of ring matter is also at a minimum. The spectral data obtained during the observation of GX1+4 are thus consistent with this interpretation.
The origin of the line at a mean energy of 522 keV is evidently due to the free annihilation of positrons and electrons. This results in the emission of two antiparallel 511 keV gamma-rays. If the source region can be characterized as a very dilute gas, the above result would not be expected since the cross-section for free annihilation is many orders of magnitude below that for positronium formation. Given the energy resolution of the present detector at 511 keV, a positronium spectrum would be highly asymmetric with a mean energy below 511 keV. As Figure 21 shows, this was clearly not observed. If the gas in the source region is sufficiently dense, positronium formed with a kinetic energy greater than its binding energy of 6.8 eV can ionize in a collision with a gas atom before annihilating. The positron may thus eventually be slowed down to energies below the threshold $E_{\text{Th}} = (K-6.8)\text{eV}$ for positronium formation, where $I$ is the first ionization potential of the stopping gas. Only free annihilation can occur for energies below $E_{\text{Th}}$. Thus the profile and mean energy of the gamma-ray line indicate that the source region has an atomic number density $10^{15}$ atoms/cm$^3$ (Leventhal, 1973). Since such densities are only found in the vicinity of condensed objects, it follows that there is a discrete source of 511 keV radiation and that this source may well be GX1+4.
The intensity of the line at a mean energy of 522 keV also provides some support for the hypothesis that a discrete source is responsible for the observed emission. As shown in Table V, a flux value of \((8.0 \pm 2.3) \times 10^{-4}\) photons/cm\(^2\)-sec was computed for this line. This is about 0.44 of the flux obtained for the feature with a mean energy of 476 keV reported by Johnson and Haymes (1973). If a discrete source of 511 keV gamma-rays coincides with GX1+4, then its intensity should have been reduced by only \(\sim 15\%\) when GX3+1 was observed in the 1971-2 flight with an instrument having a 74° FWHM beam width. A flux of \(6.8 \times 10^{-4}\) photons/cm\(^2\)-sec at 511 keV would have been readily detectable given the observing time and the efficiency of the detectors used in the 1971-2 flight. There are at least three possible explanations why a 511 keV line was not reported from the data obtained during this flight. The first is that, due to the relatively poor energy resolution of the detector, the 511 keV photopeak merged with the one at 478 keV. Secondly, the intensity of the hypothetical discrete source of 511 keV photons at GX1+4 could be variable. Finally, a new discrete source may have come into existence in the vicinity of GX1+4 between the 1971 and 1974 flights. If this last possibility should prove correct, novae in the galactic center region may be responsible. Work by Clayton and Hoyle (1974) has shown that positron-emitting nuclides such as \(^{13}\)N, \(^{14}\)O, \(^{15}\)O, and \(^{22}\)Na are created during the nova event.
Table V.

Data on the various gamma-ray lines that were detected during the observation of the discrete X-ray source GX1+4.
**TABLE V**

**Galactic Center Spectral Lines**

<table>
<thead>
<tr>
<th>Flux (10^{-4}) photons (cm^{-2}s^{-1})</th>
<th>Measured 0.1±0.1</th>
<th>Energy (MeV) 1-2-2.0</th>
<th>4.6±0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.0±2.3</td>
<td>3.7±3.1</td>
<td>26±6</td>
<td>9.5±2.7</td>
</tr>
</tbody>
</table>

**Instrumental FWHM (MeV)**

| 0.060                                    | 0.080           | 0.130                | 0.206   |

**Measured FWHM (MeV)**

| 0.07±0.02                                | 0.1             | --                   | 0.7     |

**Possible Origin**

| \(\beta^+\) Emitters | 56Fe*           | 24Mg*, 20Ne*, 28Si* | 12C*    |

**Predicted Energy (MeV)**

| 0.511                                    | 0.847           | 1.37, 1.63, 1.78     | 4.43    |

*From Rygg and Fishman 1973.*
If it is assumed that the 0.5 MeV flux is due entirely to a single line at 0.52 MeV, then the value of this flux can be compared with the results of calculations on the production of positrons from CNO nuclei emitters in the Galaxy. Ramaty et al. (1970) have made such calculations; the flux measured in the present experiment is (15 \pm 4) times larger than the largest 0.5 MeV galactic center flux that they computed. This can be taken as indirect evidence for the existence of an intense discrete source of 511 keV radiation in the vicinity of GX1+4.

The presently available data on the galactic center are thus unable to conclusively establish the correctness of any particular hypothesis. However, the data are consistent with the following: a relatively intense source of 511 keV gamma-rays is present in the vicinity of GX1+4, while a detectable excess of gamma-radiation above the continuum at a mean energy of 470 keV occurs only when the detector is looking at directions along either side of the 4 kpc ring.

2. NUCLEAR LINES

Relevant data on the various nuclear lines detected during the observation of GX1+4 are included in Table V. A small excess flux above the power law (1.2\sigma) was found at 0.9\pm0.1 MeV. This feature has a flux of (3.7\pm3.1)\times10^{-4} photons/cm^2-sec. Theory predicts that $^{56}$Fe* should be a
prominent gamma-ray source at an energy of 0.847 MeV.

Two line-like spectral features were detected at energies greater than 1.0 MeV. These are shown in Figure 27. In the energy interval from 1.2 to 2.0 MeV a spectral feature was found at a 4.1σ confidence level. The total flux above the power law is \((26\pm6)\times10^{-4}\) photons/cm\(^2\)-sec. Since the feature has a width of almost 1.0 MeV, it is too broad to be due to a single line, unless it is highly broadened. It is more probable that several lines overlap in this energy interval due perhaps to Doppler broadening. The nuclides \(^{20}\)Ne\(^*\), \(^{24}\)Mg\(^*\), and \(^{28}\)Si\(^*\) radiate in this energy interval and are all relatively abundant.

A spectral feature is present between 4 and 5 MeV; its average energy is 4.6\(\pm0.1\) MeV. The feature was detected at a 3.5σ confidence level. Since the line profile is rather asymmetric, it is quite possible that the observed average energy is slightly higher than the true energy. If the feature is indeed a nuclear line then it is most probably due to \(^{12}\)C\(^*\) which emits a 4.43 MeV gamma-ray upon de-excitation. A fit to the line shows it to be broadened by 10\%, quite possibly by the Doppler mechanism. If this interpretation is correct, then the excited, radiating nuclei have kinetic energies of \(\cdot\) 10 MeV per nucleon. This in turn provides direct evidence for the existence of low-energy cosmic rays in the general direction of the galactic center. The nuclear excitation may be plausibly attributed to the
Figure 27

Measured differential energy spectrum for GX1+4 above 1.0 MeV. Flux sums are 1.0 FWHM wide in energy. A best fit gaussian to the spectral feature at 4.6 MeV is also depicted.
interaction of these cosmic rays with the thermalized particles forming the interstellar medium. Because of solar modulation effects, the direct measurement of low-energy interstellar cosmic rays from within the heliosphere has proven very difficult.

Since the present experiment is the first to detect gamma-ray nuclear lines of extra-solar system origin, no other experimental data is available with which to compare the above results. In such a case it is imperative that the data be examined to see if some systematic effect and not a celestial source is responsible for the reported lines. A number of various tests were undertaken. In one data test, time-adjacent background counting rates at the line energies were subtracted from each other. No statistically significant differences were found. The results of these subtractions at three different energies are shown in Figure 28. In a second test of the background data, pre-transit background segment count rates at the line energies were subtracted from the corresponding post transit segments. Only segments taken at approximately the same zenith angles were subtracted from each other. Thus the differences tested for both azimuthal and time-dependent effects in the data. The results of these subtractions are shown in Figure 29. The results showed that there was no statistically significant east-west azimuthal or time-dependent asymmetry in the background data at the energies at which nuclear gamma-ray lines
Figure 28

Differences between adjacent galactic center backgrounds. This data test was undertaken to see if there were any systematic effects in the background at the nuclear line energies.
Figure 29

Zenith angle pair differences computed for galactic center backgrounds on either side of transit. This data test was undertaken to investigate possible azimuthal and time-dependent effects in the background count rates at the line energies.
ZENITH ANGLE PAIR DIFFERENCES

GX1+4

1974 APRIL 2

ENERGY INTERVAL: 1.184 TO 1.949 MEV

Figure 29

ENERGY INTERVAL: 4.019 TO 4.919 MEV

ZENITH ANGLE
were observed from the galactic center region.

In another test of the data the uncorrected partial residual count rates at the line energies were grouped into four bins in source azimuth. If an azimuthal asymmetry were responsible for the presence of the gamma-ray lines, one would expect a sinusoidal dependence upon azimuth. It was found that such fits gave values of reduced $\chi^2$ of 2.205 and 2.225 for the 1.184-1.949 MeV and 4.019-4.919 MeV energy intervals, respectively. In contrast, straight line fits to the data gave corresponding reduced $\chi^2$ values of 0.767 and 0.661. The fits to the data at the two energy intervals containing the lines are depicted in Figure 30.

As with the other data tests, these results indicate that the presence of line-like spectral features in the data is not due to azimuthal asymmetries. It should be emphasized that the 10-minute cyclic permutation of source and background segments minimizes any potential time-dependent effects in the extraction of a residual source spectrum.

C. GALACTIC PLANE SPECTRAL FEATURES

As has been noted previously, a spectrum for the galactic plane was obtained by treating three of the background segments as sources. A spectral feature at a mean energy of 470 keV was found. A residual spectrum was also computed using only the tenth background segment as a "source". This particular segment has a mean galactic
Figure 30

Straight-line and sinusoidal fits to galactic center source data grouped into four azimuth bins. This data test was undertaken to look for a possible azimuthal asymmetry; none was found.
UNCORRECTED RESIDUALS

Figure 30

ENERGY INTERVAL: 1.184 TO 1.949 MEV

ENERGY INTERVAL: 4.019 TO 4.919 MEV
latitude of only about 4° and displays rather high count rates at low energy. The resultant spectrum was fit with a power law over an energy interval extending from 0.04 to 0.90 MeV. The following expression was obtained:

\[
F(\text{photons/cm}^2\text{-sec-keV}) = (11.6 + 9.9)E^{-2.44 + 0.14}(\text{keV})
\]

For sixteen degrees of freedom, the fit gave a reduced \( \chi^2 \) value of 0.684. In examining the spectrum above 0.5 MeV, two rather interesting features were identified. In the 1.0 FWHM energy interval extending from 0.784 to 0.864 MeV, a flux of \( 2.05 \times 10^{-3} \) photons/cm\(^2\)-sec was obtained; this is \( 2.0\sigma \) above the power law. A model consisting of a gaussian superimposed on a power law was fit to a series of 0.2 FWHM flux sums over an energy interval including the spectral feature. A differential flux of \( (1.66 + 0.14) \times 10^{-5} \) photons/cm\(^2\)-sec-keV was obtained for a mean energy of \( (831 + 8) \) keV. A reduced \( \chi^2 \) value of 1.108 was obtained for 28 degrees of freedom. This fit, together with the 1.0 FWHM flux sums below 1.0 MeV, is shown in Figure 31. In the 1.0 FWHM energy interval extending from 1.117 to 1.252 MeV, a flux of \( 4.62 \times 10^{-3} \) photons/cm\(^2\)-sec was present; this is \( 2.76\sigma \) above the power law. A model consisting of a gaussian plus power law was fit to the single-channel fluxes in an energy interval containing the line. A differential flux of \( (2.5 + 1.1) \times 10^{-5} \) photons/cm\(^2\)-sec-keV was obtained at a mean energy of \( (1.15 + 0.07) \) MeV. This fit and the 1.0 FWHM flux sums for
Figure 31

Measured differential flux from the galactic plane below 1.0 MeV. The flux sums shown are 1.0 FWHM wide in energy. The best fit power law and gaussian fit to the spectral feature at .830 MeV are also shown. Only one galactic plane background segment was used as a "source" in generating the residual spectrum.
energies greater than 1.0 MeV are shown in Figure 32.

In the residual spectrum obtained using the three galactic plane backgrounds as "sources", the fluxes in the above two energy intervals were found to be $4.46 \times 10^{-4}$ and $6.96 \times 10^{-4}$, respectively, where the fluxes are in units of photons/cm$^2$-sec. These flux values are 0.735σ above the power law at the two respective energies. It would thus appear that background segment B10 is a strong source at 0.83 MeV and also at 1.15 MeV. Since only one background was subtracted from this segment to yield a residual spectrum, it might be expected that the two spectral features are simply the result of a statistical fluctuation. A statistical analysis of the various background segment count rates was undertaken for the two line energy intervals. It was found that the count rate of segment B8 (which was used as the true background) was at most 0.24σ below the mean count rate of the other background segments at these two energies. Segment B10, which was used as the "source", displayed statistically significant positive deviations from the mean of the other backgrounds, however. This segment thus behaves exactly like a true source segment.

Possible sources of the line emission are the species $^{56}$Co at 0.847 MeV and $^{44}$Sc at 1.16 MeV. Both of these nuclides, in addition to others, are created in the model of explosive supernova nucleosynthesis as developed by Clayton et al. (1969). Prominent medium-lifetime gamma-ray line fluxes were computed
Figure 32

Measured differential spectrum of the galactic plane above 1.0 MeV. The flux sums shown are 1.0 FWHM wide in energy. The best fit power law and the gaussian fit to the spectral feature at 1.16 MeV are also shown. Only one galactic plane background was used as a "source" in generating the residual spectrum.
for a supernova, \(10^6\) pc distant, that ejects \(0.14\) M_\odot of \(^{56}\)Ni. Extrapolating the \(^{44}\)Sc flux to the galactic center distance of 10 kpc gives a flux that is an order of magnitude less than that which was actually measured in the present experiment. The predicted flux is obtained if the supernova remnant is at a distance of \(\sim 3\) kpc. Alternatively, variation in the model parameters could yield an increased production of \(^{44}\)Sc so as to obtain the measured flux at a distance of 10 kpc.

The galactic coordinates of the segment B10 are 345 + 5. An optical supernova remnant, \(\text{Kes 45}\), with coordinates of 342.05 + 0.13, has been identified by Van den Bergh et al. (1973). There is an indication of a faint filamentary structure together with an extended H II region at these coordinates. At 408 MHz the remnant has an angular diameter of 30'. This implies a minimum age of 142 years, making the remnant probably too old to be responsible for the observed gamma-ray line emission. A much smaller radio source with an angular diameter of 2.5' has been identified by Kesteven (1968); its galactic coordinates are 345.34 + 1.43. Although no optical supernova remnant has been identified at these coordinates, this source can be considered a likely candidate for the line emission since its minimum age is only about 12 years.
D. MODELS

A considerable amount of information can be obtained from an analysis of the nuclear gamma-ray lines which are produced by the interaction of cosmic rays with the interstellar medium. In particular, given suitable theoretical models, an estimate of the index of the low-energy cosmic ray spectrum in the galactic center region can be obtained. Also, with additional data, it will be possible to determine the approximate distribution of low-energy cosmic rays in the Galaxy.

To realize the first of these objectives it is necessary to develop theoretical models which give the dependence of the various nuclear gamma-ray line fluxes upon the spectral index of the low-energy cosmic rays. This has been accomplished by Rygg and Fishman (1973). Using the nuclear line data listed in Table V, the ratio of the $^{12}$C line flux to the sum of the $^{20}$Ne*, $^{24}$Mg*, and $^{28}$Si* line fluxes can be computed. Comparing this value to the results obtained by Rygg and Fishman implies a low-energy cosmic ray spectral index of 3.2 ± 0.5. This range of values for the power law index is thus somewhat steeper than the 2.6 value of the index that characterizes the spectrum of the high-energy galactic cosmic rays. Rygg and Fishman predicted that the 6.13 MeV line due to $^{16}$O* should have a flux 0.35 that of $^{12}$C*. However the present experiment failed to detect any flux at this energy. The observed counting rate at 6.1 MeV corresponds
to a flux of \((-3.7 \pm 2.8) \times 10^{-4}\) photons/cm\(^2\)-sec. Meneguzzi and Reeves (1973) calculated that the ratio of the \(^{56}\text{Fe}^*\) flux at 0.847 MeV to the \(^{12}\text{C}^*\) flux at 4.43 MeV should be \(\approx 1\). Rygg and Fishman (1973), assuming an index of 2.5 for the cosmic ray spectrum, predicted a value of 0.1 for this ratio. From the present experiment a value of \((0.4 \pm 0.4)\) was obtained for this ratio. The great uncertainty is due to the low statistical significance of the 0.9 MeV feature. The need for additional observations of the galactic center region at gamma-ray nuclear line energies is evident.

Analysis of the nuclear line data is also useful in trying to determine the distribution of low-energy cosmic rays in the Galaxy. The following equation is useful in developing a simple model of the emitting region:

\[
P(\text{cm}^{-2}\, \text{sec}^{-1}) = \left(\frac{1}{4\pi r^2}\right) V n_p \phi_c P
\]

where \(V\) is the volume of the emitting region, \(n_p\) is the interstellar proton density within \(V\), \(r\) is the distance to \(V\), \(\phi_c\) is the differential flux of 10 MeV/nucleon \(^{12}\text{C}\) nuclei, and \(P\) is the production constant for the nuclear reaction. Rygg and Fishman (1973) have shown that \(P = 4.2 \times 10^{-24}\) cm\(^2\) MeV and that it is relatively independent of the cosmic ray spectral index \(\alpha\) for values of \(\alpha\) in the 2.0-4.0 range. Using the measured value for \(F\) in Table V and taking \(r = 3 \times 10^{22}\) cm, it follows that
\[ \phi_{c \, n_p \, V} = 3 \times 10^6 \text{ cm}^{-2} \text{ sec}^{-1} (\text{MeV/nucleon})^{-1} \]

where it is assumed that \( n_p \) is constant throughout the volume \( V \).

If low-energy cosmic rays are of uniform flux throughout the entire Galaxy and \( n_p \sim \text{ cm}^{-3} \), then \( \phi_c \sim 3 \text{ cm}^{-2} \text{ sec}^{-1} (\text{MeV/nucleon})^{-1} \). This value of \( \phi_c \) is in agreement with an extrapolation of the \(^{12}\text{C}\) flux observed in high-energy cosmic rays down to an energy of 10 MeV/nucleon (assuming an \( E^{-2.6} \) power law). This simple model of a uniform distribution is not likely to be correct because the mean energy density in cosmic rays would be far greater than that allowed by the general dynamics of the interstellar medium (Ramaty, et al. 1970).

If the emitting volume is a sphere of radius \( \sim 300 \text{ pc} \) at the center of the Galaxy, as suggested by Ginzburg and Khazan 1972), then \( \phi_c \) will be about \( 10^2 \) times larger than the low-energy flux estimated from the \( E^{-2.6} \) extrapolation. This assumes that \( n_p \sim 10 \text{ cm}^{-3} \). If \( n_p \sim 1 \text{ cm}^{-3} \) and the volume \( V \) is the same as that observed to be emitting high-energy gamma-rays by the SAS-2 experiment (Fichtel et al. 1975), then \( \phi_c \sim 10 \text{ cm}^{-2} \text{ sec}^{-1} (\text{MeV/nucleon})^{-1} \) at an energy of 10 MeV/nucleon. This value for \( \phi_c \) is about three times the extrapolated flux of \(^{12}\text{C}\) in cosmic rays. However if \( n_p \sim 4 \text{ cm}^{-3} \) as Stecker et al. (1975) have suggested for the vicinity of the 4 kpc ring, then the value of \( \phi_c \) would be equal.
to that predicted by the power law. It is clear that mapping measurements at MeV energies are needed to accurately determine the angular extent of the emitting region.
VI. CONCLUSIONS

A region with a diameter of $13^\circ$ centered on the discrete X-ray source GX1+4 was found to be emitting a power law continuum. Superimposed on this continuum are at least three spectral features strongly resembling gamma-ray lines. The feature at 0.5 MeV is very probably the result of electron-position annihilation in the vicinity of a condensed object. Although the data cannot confirm it, a recent nova event in the galactic center region is probably responsible for the production of the $\beta^+$ emitting nuclei.

Spectral features at higher energies were also found to be present. The probable sources of these line-like features are the relatively abundant isotopes produced by nucleosynthesis. The present data supports the hypothesis that these lines are produced by the interaction of low-energy cosmic rays with the interstellar medium. It should be emphasized that all of the spectral lines detected in the present experiment were expected on the basis of theoretical models. From the ratios of the line fluxes, an estimate for the spectral index of low-energy cosmic rays in the galactic center region was obtained. Additional observational data will be necessary if the extent of the region responsible for the emission of the nuclear gamma-rays is to
be accurately determined.

Analysis of the background segments taken when the galactic plane was within the field of view revealed the presence of a spectral feature at a mean energy of 470 keV. This data, together with that obtained from previous flights, implies that a detectable excess above the continuum at 470 keV occurs only when the detector is looking at directions along either side of the 4 kpc ring structure. The data are consistent with the hypothesis that the 470 keV feature is due to $^7\text{Be}^*$ and $^7\text{Li}^*$ nuclei radiating at 432 keV and 478 keV, respectively.

Analysis of one of the background segments taken in the galactic plane showed it to display enhanced count rates at energies near 0.847 MeV and 1.16 MeV. At least two suspected supernova remnants were within the field of view of the detector during this segment. The flux at 1.16 MeV is consistent with the prediction of a theoretical model for explosive nucleosynthesis in a supernova.

A very considerable amount of new information was obtained from the data provided by the present experiment. However, additional observations of the galactic center region with an even more sensitive detector are clearly indicated.
REFERENCES


145


