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OBSERVATION OF GAMMA-RADIATION FROM THE GALACTIC CENTER REGION*

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ABSTRACT

A balloon-borne investigation of the region in the vicinity of the galactic center was performed with a γ-ray telescope having an angular resolution of about $1\frac{1}{2}°$ above 15 MeV. A narrow band of emission about 3° wide, lying along the galactic equator, was observed over the atmospheric background, and confirms the detection of galactic γ-radiation first observed above 100 MeV from OSO-3. The integral intensity above 15 MeV is about 3.5×10^{-4} γ cm^{-2} s^{-1} rad^{-1}, but is dependent on the assumed spectrum. A comparison with the measurements above 100 MeV indicates that at least 50 percent of the radiation comes from the decay of π^0 mesons produced in cosmic-ray collisions on interstellar gas. The possibility that point sources also contribute to this excess cannot be ruled out; however, we are unable to confirm the existence of any of the reported γ-ray sources within 20° of the galactic center. Our results suggest that either these suspected sources are variable or they have hard emission spectra (e.g., π^0 decay).

Subject headings: cosmic rays — gamma rays — interstellar matter — X-ray sources

I. INTRODUCTION

Gamma-ray astronomy emerged as an observational science when a telescope on board the OSO-3 satellite detected the emission of photons above about 100 MeV from the plane of the Galaxy (Clark, Garmire, and Kraushaar 1968; Kraushaar *et al.* 1972). The γ-rays appeared to come from a diffuse band within $\pm 15°$ of the galactic equator and exhibited a broad maximum in galactic longitude toward the galactic center. The intensity in directions away from the galactic center ($30° < l^{\text{II}} < 330°$) could be explained by the decay of π^0 mesons produced in cosmic-ray collisions on interstellar gas. In the direction of the galactic center, the observed flux was significantly above the calculated intensity from π^0 decays. Because of the limited angular resolution ($\pm 15°$) of the OSO-3 detector, the authors were unable to investigate the possibility that this enhanced emission was due to the presence of point sources in the vicinity of the galactic center.

Gamma-ray emission from the vicinity of the galactic center has also been investigated by balloon-borne instruments. Kniffen and Fichtel (1970; Fichtel *et al.* 1972) reported about a $4\,\sigma$ enhancement over background within $\pm 6°$ of the galactic equator. Their measured intensity above 100 MeV was in good agreement with the flux observed from OSO-3. They also set a limit on the flux emitted between 50 and 100 MeV which suggested that π^0-decay γ-rays were the dominant source of the emission.

In contrast, observations made by Frye *et al.* (1971*a*) during a series of balloon flights over Australia have not confirmed the emission of diffuse γ-radiation from the galactic plane. From these observations, upper limits were placed which were considerably below the reported intensities. Two other groups have recently searched unsuccessfully for the diffuse emission from the plane (Dahlbacka, Freier, and Waddington 1973; Browning, Ramsden, and Wright 1972). Browning *et al.* have suggested, however, that point sources which they claimed to have observed could produce the apparent diffuse intensity measured from OSO-3.

In this paper, we report results of an investigation of the galactic center region with a detector sensitive to γ-rays above about 10 MeV and having an angular resolution of about $1\frac{1}{2}°$ above 15 MeV. These measurements confirm the emission of γ-radiation from along the galactic equator and, furthermore, indicate that the radiation is concentrated in a narrow band, about 3° wide, in the vicinity of the galactic center. A composite energy spectrum of this emission is derived from this low-energy observation and from the observations above 100 MeV. We also discuss our investigation of the various suspected point sources reported in the vicinity of the galactic center.

II. THE EXPERIMENT

a) *Design*

We designed the experiment with the dual goals of attaining high angular resolution (1°–2°) and good energy resolution ($\leqslant 25\%$) for γ-rays above 10 MeV. To date, only instruments operating at photon energies above 100 MeV have been able to attain this angular resolution. For energies below 100 MeV, the angular resolution of these instruments deteriorates due to multiple Coulomb scattering of the electrons produced

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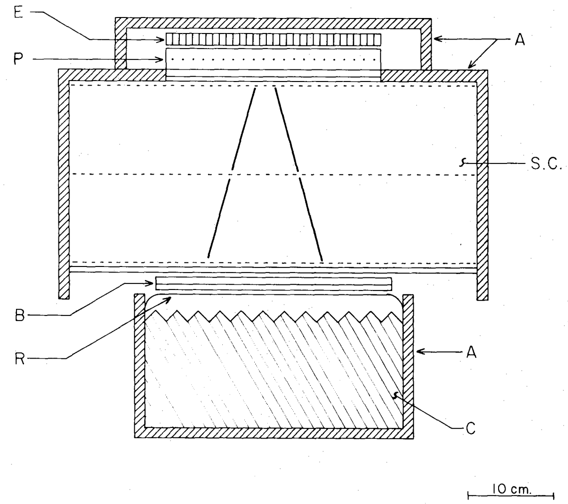

FIG. 1.—Drawing of the telescope showing an electron pair in the wide-gap spark chamber (S.C.) (A) plastic anticoincidence counters; (E) 650 cm² × 1.25 cm emulsion stack; (P) multiwire proportional counter; (B) two plastic coincidence counters; (C) absorption-Cerenkov counter of clear Plexiglas (15 g cm^{-2}). Cerenkov light from upcoming particles is reflected by (R) onto phototubes (*not shown*) imbedded in the block.

in the γ-ray interactions. To overcome this limitation, our telescope incorporated a nuclear emulsion stack as a converter for the γ-rays. This concept is similar to the one adopted by May and Waddington (1969) for γ-rays with energies above 100 MeV. It is based on the ability to locate the electrons produced in the γ-ray interactions in the emulsion from measurements made on their trajectories in a spark chamber. By microscopically following the tracks of these electrons back to their origins in the emulsion, measurements can be made on the electrons before they had been scattered appreciably. To use this procedure down to γ-ray energies near 10 MeV, the amount of material between the "active" sections of the emulsion and spark chamber had to be minimized (Kinzer, Seeman, and Share 1968). This was necessary so that the electrons would not change their directions significantly between these two elements of the telescope.

A drawing of the configuration of our telescope is shown in figure 1. Gamma rays incident from above interact in a nuclear emulsion stack (650 cm² × 1.25 cm), producing electron pairs and Compton-recoil electrons. When these electrons leave the emulsion, they are detected by a multiwire proportional counter (P) containing a gas mixture of 90 percent argon, 10 percent methane. The proportional counter was used in lieu of a scintillation counter because of its low mass features; it was constructed with 90 percent transparent wire-mesh electrodes and with Mylar windows only 0.006 mm thick. The requirement that the electrons not be scattered appreciably before their trajectories could be measured in the spark chamber also prompted us to employ a wide-gap spark chamber (S.C.), having an entrance window only 0.006 mm thick and a 90 percent transparent top electrode made of 0.025 mm steel mesh. The chamber had two 10-cm-wide gaps, contained a gas filling of 90 percent Ne, 10 percent He, and operated at a pulsed voltage of about 80 kV.

Below the spark chamber were located two 0.63-cm-thick plastic scintillation counters (B) which in coincidence with the proportional counter registered the presence of charged particles passing through the emulsion and spark chamber. Surrounding most of the telescope were plastic anticoincidence counters (A) which rejected incident charged cosmic radiation. These counters included a cup over the emulsion stack and proportional counter, and a cup below and around the range-Cerenkov counter (see below). In addition, the walls and top lid of the spark chamber (excluding the entrance window) were also made of plastic scintillators and formed part of the anticoincidence shield. This feature also helped to reduce background from neutral particles converting in the walls of the chamber.

The range-Cerenkov counter (C) consisted of a block of clear UVT Plexiglas, 15 g cm^{-2} thick, which was designed to stop electrons with energies less than $\sim$40 MeV. Higher-energy electrons were able to pass through the block and reach the anticoincidence counter, thereby causing the event to be rejected. This feature restricted the telescope's sensitivity to a range in energy between about 10 MeV and about 200 MeV. Unfortunately, the block also served as a converter for upward-moving albedo γ-rays. These photons would also be detected if the electrons they produced were absorbed in the emulsion stack. In order to reduce sensitivity to those events, five photomultipliers were embedded in the block and viewed a diffuse reflector (R) placed above them. Cerenkov radiation produced in the block by the upward-moving electrons was reflected by (R) back onto the faces of the phototubes. Because of the limited collection area presented by the tubes, only about 50 percent of the albedo γ-rays converting in the block and otherwise detected by the system were rejected by this Cerenkov anticoincidence counter.

The occurrence of a γ-ray type event was therefore marked by a coincidence between the proportional counter (P) and the two scintillation counters (B), unaccompanied by pulses from any of the anticoincidence counters (A) or from the Cerenkov counter (C).

Images of the spark-chamber events were recorded in 90° stereo on 35-mm film. Fiducials marking the location of the emulsion stack were illuminated by a xenon flash tube via fiber-optics light guides. Also exhibited on the film was the time of the event, information on the energy loss of the particles passing through the scintillation counters (B), and a marker flagging the presence of any charged particle passing through the system in the previous 6 μs (thereby identifying possible muon-decay events). In order to reduce

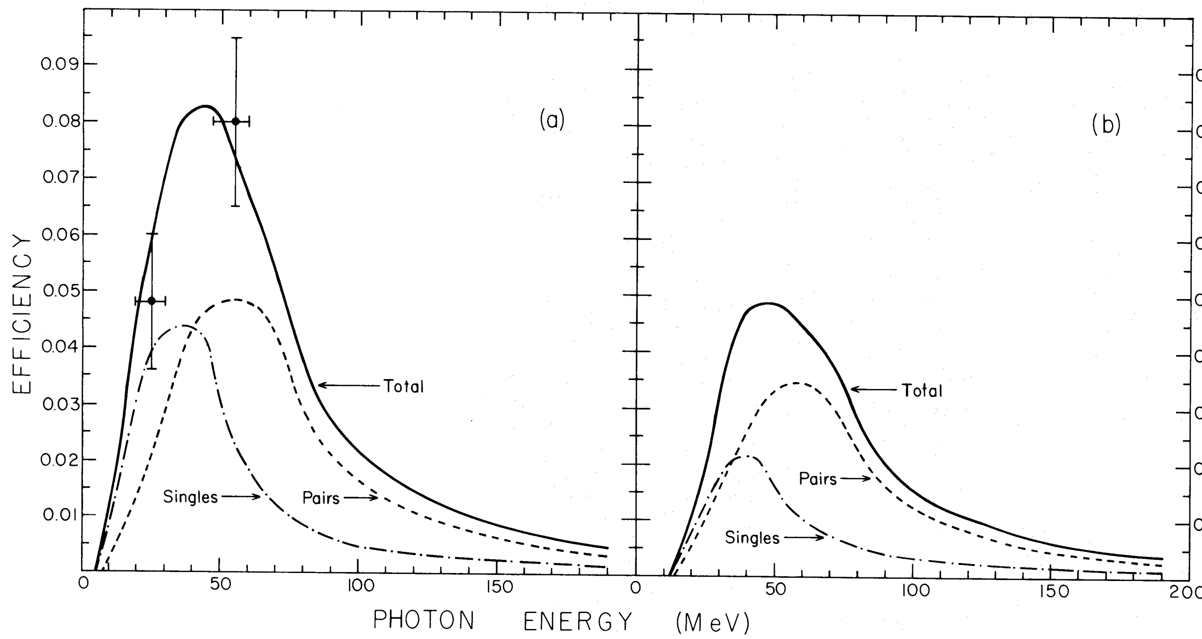

FIG. 2.—The calculated efficiency of the telescope as a function of energy for γ-rays incident at 0°. Efficiencies are plotted separately for events exhibiting pairs (*dashed line*) and single tracks (*dot-dash line*) in the spark chamber. (*a*) Efficiency when only spark-chamber data are used; the experimental points were obtained from a calibration at the NRL Linac. (*b*) Efficiency when events are followed back into the emulsion stack.

damage to the phototubes viewing the spark chamber walls and exposed to the intense sparks, the voltage difference between the first and second dynodes of each tube was reduced to zero prior to activating the chamber.

Single and coincidence counting rates were telemetered to the receiving station along with housekeeping information and measurements of the ambient pressure, obtained by two independent sensors. In addition, this radio link was used to monitor the aspect of the telescope and to update the on-board computer controlling the telescope's orientation.

The telescope was maintained at sea-level pressure in a 0.16-cm-thick aluminum sphere 5 feet in diameter surrounded by a thermal blanket of polyurethane foam. The sphere was mounted in an altazimuth orientor which used magnetometers for reference and an analog computer for pointing the telescope at possible γ-ray sources. A gas jet system was employed to control the system in azimuth, while an electric motor drove the system in elevation.

b) *Calibration*

The sensitivity of the telescope as a function of γ-ray energy and incident angle has been calculated using a Monte Carlo program. The program is based on an earlier routine developed by Dennis and Share (1967) which has been improved to permit calculations down to energies near 10 MeV and to allow for γ-ray conversions via the Compton process. In contrast to the earlier routine in which a "continuous slowdown" was assumed for electron energy losses, the current program treats ionization and precipitous bremsstrahlung energy losses separately. It also determines the disparity in energy of the electrons formed in pair production without resorting to a simplified approximation and, furthermore, folds in the kinematic opening angle of the electron pairs and the scattered direction of the recoil Compton electrons.

Plotted in figure 2*a* is the calculated efficiency of the telescope as a function of energy for photons incident at 0°. The curve marked "pairs" represents the efficiency of observing an electron pair in the spark chamber. In making this estimate, we have taken into consideration the known multiple track properties of the spark chamber. The curve marked "singles" represents the efficiency for observing a single electron track in the spark chamber resulting from a γ-ray interaction in the emulsion. This type of event arises either from Compton collisions or from pair-production interactions in which only one of the electrons emerges from the emulsion and is visible in the spark chamber. The calculated efficiencies have been multiplied by a factor of about 0.80 to take into consideration those events rejected because they triggered the Cerenkov anticounter (see fig. 1; this could happen if, e.g., the electron hit one of the phototubes embedded in the Plexiglas block).

The telescope has a threshold energy of about 10 MeV, above which the efficiency rises rapidly to a maximum and then falls off with increasing energy. This decrease is due to the rejection of events in which the electrons pass through the energy-absorbing block and trigger the anticoincidence cup (see fig. 1). As expected, the efficiency for pairs peaks at a higher energy than that for singles.

A calibration of the telescope has been performed at the NRL electron Linac. "Monoenergetic" γ-rays of about 25 and 55 MeV were derived from this facility using the high-energy tail of bremsstrahlung produced when 30- and 60-MeV electrons from the linac struck a thin target. A high-efficiency plastic scintillator was placed behind and in contact with the target, and was operated in anticoincidence with the telescope. This allowed only those events to be detected in which the incident electron lost almost all its kinetic energy to the bremsstrahlung γ-ray. The absolute efficiency of our telescope was determined from a comparison of its response to that of a nearly "100 percent" efficient detector (a 12″ × 12″ NaI crystal or a lead-scintillation shower detector).

Plotted near 25 and 55 MeV in figure 2*a* are the total efficiencies determined by this calibration. The uncertainties shown in the measured values are due to both statistical and systematic errors. Agreement with the calculation is quite acceptable.

The angular response of the telescope is dependent on the scattering of electrons as well as on its geometry. We have calculated this response using our Monte Carlo program and have also measured it during our accelerator calibrations. For γ-rays with energies near 55 MeV the agreement between the two procedures is good. For an assumed atmospheric spectrum (Beuermann 1971), our calculations indicate that the telescope has an effective aperture of about 50° (FWHM).

Shown in figure 2*b* is the calculated efficiency of the telescope when the analysis involving the nuclear emulsion stack is included. In this Monte Carlo calculation, we have folded in the estimated probability of locating the electrons in the emulsion as a function of their energy when they left the stack. Consideration is also given to the distribution of angles of these electrons because the location procedure becomes more difficult for tracks making large angles with the plane of the emulsion. Once again, the efficiencies are shown separately for events exhibiting both tracks of an electron pair in the spark chamber or just a single track. A comparison with figure 2*a* reveals that the effective energy threshold of the telescope is higher when the emulsion analysis is performed and, furthermore, that the efficiency of the telescope is reduced by about a factor of 2.

c) *The Balloon Flight*

The data presented in this paper were obtained during the "Galaxia '71" expedition to Paraná, Argentina. Paraná is located at a latitude of $-31\overset{\circ}{.}8$ and a longitude $-60\overset{\circ}{.}5$. At this location the vertical cutoff rigidity for primary charged cosmic radiation is estimated to be about 11.5 GV (Shea and Smart 1973).

The experiment was carried aloft by a 5.7×10^5 m^3 balloon which was launched at 09:49 UT on 1971 December 1. Data rates obtained during ascent were transmitted by telemetry and were recorded on magnetic tape. When the balloon reached an atmospheric depth of about 23 g cm^{-2}, the spark chamber was activated, permitting an investigation of the growth of secondary γ-radiation in the atmosphere. These data are discussed in separate papers which we are preparing concerning atmospheric photons and extraterrestrial diffuse γ-radiation (see also Share, Kinzer, and Seeman 1973; Seeman, Share, and Kinzer 1973).

The balloon reached an atmospheric depth of about 3 g cm^{-2} at 12:50 UT, at which time the telescope was pointed to within about $1\frac{1}{2}°$ of the location of the reported variable source Libra γ-1 (Frye *et al.* 1971*b*). The balloon continued to ascend slowly, reaching a minimum depth of about 2.2 g cm^{-2}. At 14:50 UT the telescope was oriented to point within about $2\frac{1}{2}°$ of the galactic center. This orientation was maintained for a period of about 2 hours, after which time the gas for the azimuth control system was depleted. The telescope was then rotated back to the vertical to permit a drift scan of a region within 30° of the galactic center. This scan continued for a period of about $2\frac{1}{2}$ hours, at which time the flight was terminated.

The aspect of the telescope during the flight was determined by both coarse and fine magnetometers. The *coarse* magnetometer had a resolution of about $\pm 2°$, while the resolution of the *fine* magnetometer was $\pm 0\overset{\circ}{.}2$. During a previous flight in 1969 (Kinzer *et al.* 1971), the aspect obtained with this system was compared with the aspect obtained from star-field photographs. Agreement between the two methods was better than $0\overset{\circ}{.}5$. For this reason we estimate that the uncertainty in aspect during the entire flight over Argentina in 1971 is less than $0\overset{\circ}{.}5$.

d) *Data Analysis*

About 12,000 photographs of spark-chamber events were taken while the experiment floated under less than 3 g cm^{-2} of residual atmosphere. At least 97 percent of these pictures exhibited identifiable tracks, and of these about 12 percent show the presence of two tracks appearing to originate from a common origin in the emulsion stack. The majority of these two-track events are electron pairs arising from the γ-ray interactions in the emulsion. The dominant part of the data upon which this report is based comes from an analysis of these downward "pair" events.

Initially, hand measurements were made, with an accuracy of about $\frac{1}{2}°$, on the tracks of the electron pairs in the spark chamber. The energies of the electrons were estimated from measurements of their scattering in the 0.125-mm aluminum central electrode of the spark chamber. A track scattering about 1° (projected angle) in this amount of aluminum corresponds, on the average, to an electron with an energy of about 10 MeV. Using these energies, rough estimates of the directions of the incident γ-rays could be obtained from the weighted directions of the electrons. After folding in the aspect of the telescope, we were able to make a celestial map of the observed γ-radiation above about 10 MeV with an angular uncertainty of $\sim 13°$ FWHM. In the investigation of specific γ-ray sources, this map was used to select events which we would attempt to locate in the emulsion. Because of the difficulty in following low-energy electrons from the spark chamber back into the emulsion, we restricted the events to those having at least one electron with an energy above about 10 MeV as measured in the spark chamber.

For the selected events, accurate coordinate measurements were then made on the electron trajectories in the spark chamber by using an image-plane measuring machine. (Details of the location procedure can be found in an earlier publication, Kinzer, Seeman, and Share 1969.) Typically a 1 mm × 1 mm area was microscopically scanned about the predicted location of the electron track near the bottom edge of the emulsion. Special procedures, discussed by Kinzer *et al.* (1968), were employed to permit the emulsion to be scanned to within 40 μ of the edge. Tracks found in the emulsion within about $\pm 4°$ of the predicted directions were followed in order to determine whether they originated in a γ-ray interaction. When a pair was located, we made a detailed comparison of each electron's position, angle, and energy in the emulsion with the corresponding parameters obtained from measurements in the spark chamber. We estimate that an electron pair observed in the spark chamber and then located in the emulsion has a greater than 95 percent chance of being correctly matched. Measurements made on these matched electron tracks near the point of conversion in the emulsion allow the arrival direction of the γ-ray to be determined to about $1\frac{1}{2}°$, and its energy to be estimated to within (+30, −16) percent (more accurate energy determinations could be made if desired).

As we mentioned above, only about 12 percent of the events photographed in the spark chamber exhibit what appear to be electron pairs. The remainder are predominantly single-track events. Some of these single-track events, on the order of about 1000, are expected to have been produced in the emulsion by downward-moving γ-rays interacting via Compton collisions, or via pair-production interactions in which only one of the electrons emerges from the emulsion and is visible in the spark chamber. In order to make use of this type of event for γ-ray research, we must be able to distinguish it from the large background of similar events produced by other sources.

About 10 percent of all the single tracks photographed have been identified, from their high rate of ionization in the two coincidence counters [see (B) in fig. 1], as slow protons produced by neutrons interacting in either the emulsion stack or Plexiglas block. The remaining 9000 single-track events are interpreted to be electrons and can be further differentiated depending on an estimate of their energies in the spark chamber. About 7600 of these tracks scatter more than 1° (projected angle) in the 0.125-mm central electrode of the chamber and are therefore likely to possess energies less than about 10 MeV. The most likely source for these electrons are splash albedo γ-rays from the atmosphere which converted in the Plexiglas block, producing upward-moving electrons that stopped in the emulsion and were not rejected by the Cerenkov counter.

A large fraction of the remaining 1400 single-track events, with energies greater than about 10 MeV, are likely to have been produced by downward-moving γ-rays interacting in the emulsion. It is therefore reasonable to search for these electron tracks in the emulsion in order to locate the γ-ray interaction. We estimate that single electron tracks observed in the spark chamber and then located in the emulsion have a better than 85 percent chance of being the correct candidates. Only eight of these single electron tracks have been located to date in our emulsion analysis. They have been included in the sample of γ-ray events which we shall discuss in the next section. In our further analysis of the flight, we hope to improve the statistical significance of our data by including many more of these single-track events.

III. RESULTS

We shall first summarize the low angular resolution ($\sim 10°$) data obtained with the spark chamber alone. Then we shall describe the more revealing high-resolution ($1\frac{1}{2}°$) data obtained by locating the γ-ray interactions in the emulsion.

a) Spark-Chamber Analysis

A total of 1094 spark-chamber events showing what appear to be downward electron pairs were photographed while the balloon floated at an atmospheric depth of about 2.5 g cm^{-2}. Using these pairs, a region of the celestial sphere within declination $-60° \leqslant \delta \leqslant +10°$ and right ascensions $180° \leqslant \alpha \leqslant 320°$ was investigated for possible sources of γ-radiation greater than 10 MeV. This was done by comparing the observed number of events within 10° of the sources with those calculated by assuming that all the electron pairs observed came from atmospheric γ-rays. In this calculation the angular response of the detector, as well as the variation of atmospheric γ-radiation with zenith angle, was folded into the exposure that the detector had to different source regions. We have not found any regions at this resolution for which the observed number of events exceeded the calculated number by more than 2–3 standard deviations. This places upper

TABLE 1

SUSPECTED POINT SOURCES NEAR THE GALACTIC CENTER

Reported by	Identification	Galactic Coordinates l^{II} (degrees)	Galactic Coordinates b^{II} (degrees)	Flux > 100 MeV ($\times 10^{+5}\ \gamma$ cm^{-2} s^{-1})	NRL Results ($\times 10^{+5}\ \gamma$ cm^{-2} s^{-1}) > 10 MeV*	NRL Results ($\times 10^{+5}\ \gamma$ cm^{-2} s^{-1}) > 15 MeV†
Case-Melbourne						
(Frye *et al.*).........	Sgr γ-1	0	−18	1.5 ± 0.5	< 16	< 10
	Gγ 2+3 (GX 1+4?)	2	+ 3	1.5 ± 0.5	< 22	< 6
	Gγ 341+1 (GX 340−2?)	341	+ 1	1.6 ± 0.5	< 36	< 12
	Libra γ-1 (PKS 1514−24?)	340	+30	2.4 ± 0.6 < 1.5	< 25	< 8
Southampton						
(Browning *et al.*)....	2U 1833−05?	26.5	+ 1.5	2.9 ± 0.8	< 35	< 12
	2U 1813−14?	17.5	+ 3.5	1.8 ± 0.5	< 43	< 8
	2U 1728−16?	9.5	+ 6.5	2.1 ± 0.6	< 47	< 6
Minnesota						
(Dahlbacka *et al.*)...	?	352	+16	2–5	< 32	< 8

* Angular resolution ~10°. † Angular resolution ~$1\frac{1}{2}$°.

limits (2 σ) of about $3 \times 10^{-4}\ \gamma$ cm^{-2} s^{-1} on the flux above 10 MeV from any point sources (see table 1; an integral spectrum $\propto E^{-1}$ was assumed). The spark-chamber events were also investigated for evidence indicating a concentration along the galactic equator. Shown in figure 3 are the number of electron pairs observed as a function of galactic latitude for a range in longitude 328°.5 < l^{II} < 32°.5. The curve represents the expected number of events, assuming that they are due to atmospheric γ-rays. A small excess, a little over one standard deviation, occurs in a band within ±12°.5 of the galactic equator. This excess corresponds to an equivalent "line" intensity on the order of $3 \times 10^{-4}\ \gamma$ cm^{-2} s^{-1} rad^{-1}.

b) *Emulsion Analysis*

Our analysis of data from the nuclear emulsion stack is only partially completed; however, it has already uncovered significant results concerning γ-ray emission from along the galactic plane and has also produced a sensitive survey of possible point sources in the vicinity of the galactic center.

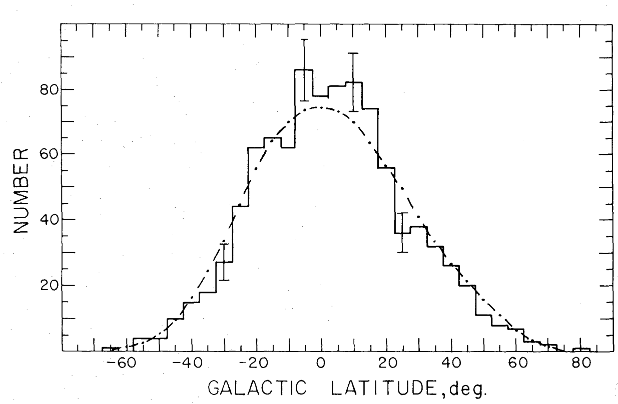

FIG. 3.—Distribution of pair events observed in the spark chamber as a function of galactic latitude. The curve represents the expected distribution assuming the γ-rays are of atmospheric origin; it is normalized to the total number of events observed.

There are about 2500 photographed events in the spark chamber which can be attributed to downward-moving γ-rays. Of these, 1094 are apparent electron pairs, and the remaining are straight single electron tracks. Because of the less ambiguous nature of the pair events, we have concentrated most of our early efforts in locating these events in the emulsion.

In determining which events to search for in the emulsion, we have used the directional and energy information obtained from the spark-chamber photographs. For the investigation of γ-radiation from the galactic plane, only events appearing to come within ±20° of the galactic equator have been selected for further analysis. We estimate that this sample should contain about 90 percent of the γ-rays detected which were emitted from along the galactic equator. The electrons produced by the remaining γ-rays will have been scattered sufficiently so that their apparent origins, as determined by spark-chamber measurements, lay outside the ±20° band. Measurements on the scattering of the electron tracks in the spark chamber have aided us in restricting our search only for events in which one of the electrons is more energetic than 10 MeV. As we discussed earlier, attempts at locating lower-energy electrons in the emulsion are in general fruitless.

To date, we have completed a search in the emulsion for all electron pairs in the spark chamber which appear to come within ±10° of the galactic equator and for about 30 percent of the pairs appearing to come within 10°–20° of the equator. We have also searched for about 10 percent of the high-energy single-track events appearing to come within 10° of the equator.

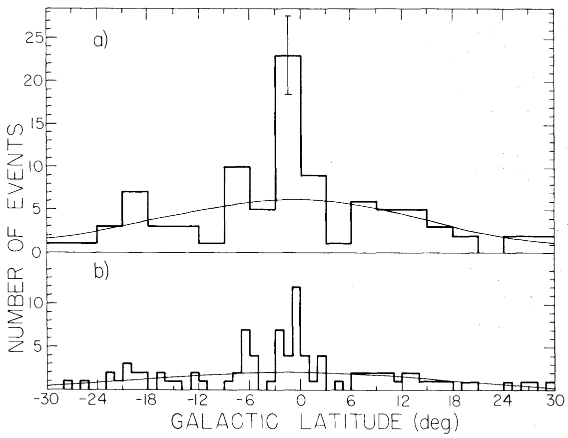

FIG. 4.—Distribution of γ-rays as a function of galactic latitude from high resolution measurements made in the stack of emulsion. The curves represent the numbers expected if the γ-rays were atmospheric in origin and are normalized to the observations for $|b^{II}| > 6°$. (*a*) 3° resolution in latitude; (*b*) 1° resolution in latitude.

From this sample of events, 98 γ-rays have been located in the emulsion, and in all but one of these events the γ-ray interacted via the pair-production process (there was one Compton collision). Of the 98 events, 90 were located from photographs showing both members of an electron pair in the spark chamber, while the remaining eight events were located from photographs showing only one electron.

The galactic coordinates of the arrival directions of these γ-rays have been determined to within about $1\frac{1}{2}°$. Plotted in figures 4*a* and 4*b* are histograms showing the numbers of γ-rays observed in 3°-wide and 1°-wide strips of galactic latitude for a range in longitude $320° < l^{II} < 40°$. Represented by the curves is the latitude distribution expected on the assumption that the observed γ-rays are atmospheric in origin. This distribution was generated by a computer simulation of the entire flight which determined, at 60-s time intervals, the exposure of the telescope to celestial sources. Folded into the simulation were the orientation and atmospheric depth of the telescope at the time of observation, the zenith-angle distribution of atmospheric γ-rays, and the calculated angular response of the telescope to an atmospheric γ-ray spectrum. Also included were the angular and energy restrictions placed on the spark-chamber events selected for further analysis in the emulsion, and the probability of locating electrons at these angles in the emulsion. The calculated curves have been normalized to the number of events observed outside 6° from the galactic plane in order to reflect the expected background intensity along the plane.

The observed distribution of events shows a prominent excess within $\pm 3°$ of the galactic equator. Within this 6° band we would have expected only 13 events from the atmosphere, whereas we observed 32. We estimate that the probability of observing this large an excess from a random distribution is less than one part in 10^5.

A large part of this excess is contained within a band about 3° wide. A width this narrow precludes the possibility that our initial selection of spark-chamber events, within 20° of the galactic equator, could have produced this effect. It therefore appears that the galactic γ-ray emission near the galactic center comes from a narrow band, possibly as small as 3° in width.

There is some indication that the emission may not be centered on the galactic equator. However, this could be due to a systematic error in determining the direction of the γ-rays or to limited statistics. The excess observed near $-6°$ in latitude is attributable to five events occurring within the $1\frac{1}{2}°$ resolution of the telescope and will be discussed below.

We have estimated the integral γ-ray flux above 15 MeV appearing to come from the narrow band along the galactic equator. In doing this we used our Monte Carlo routine for folding in the telescope's response to γ-rays assumed to be emitted uniformly from this band over a longitude range $330° < l^{II} < 30°$ and following two different energy spectra: (*a*) an $E\gamma^{-2}$ differential spectrum representative of Compton collisions and (*b*) the decay spectrum of neutral pions produced in collisions of cosmic rays with interstellar gas. Because of its rejection of high-energy γ-rays, the detector has a greater efficiency for photons following the power-law spectrum. Therefore, the equivalent line intensity above 15 MeV for the power-law spectrum is $2.4 \times 10^{-4}\ \gamma\ cm^{-2}\ s^{-1}\ rad^{-1}$ while it is $4.6 \times 10^{-4}\ \gamma\ cm^{-2}\ s^{-1}\ rad^{-1}$ for the π^0 spectrum. We estimate that there is an uncertainty of about 40 percent in each of these values due to statistics and uncertainties in our knowledge of the total efficiency of the telescope.

Shown in figure 5 is a galactic map of the source locations of the 98 γ-rays located in our investigation of emission from along the galactic plane. Due to the aperture of the telescope (FWHM $\sim$ 50°), the exposure to the region shown in the map was not uniform. The dashed curves give the contours inside of which the telescope had relative exposures greater than 75 percent of the maximum (inner contour) and greater than 50 percent of the maximum. The $1\frac{1}{2}°$ uncertainty in incident γ-ray directions is represented by the open circles.

There appears to be a concentration of events along the equator between galactic longitudes of 350° and 360°. Of the total of 32 events observed within $\pm 3°$ of the equator, 11 fall within this region. Our limited statistics prevent us from determining whether this concentration is due to the presence of point sources. However, there are two locations at which at least four events fall within the $\sim 1\frac{1}{2}°$ angular uncertainty of the telescope. Only about 0.5 event is expected to fall randomly within such a circle of uncertainty in this region. An excess of four events, if attributed to a point source, would correspond to an intensity of

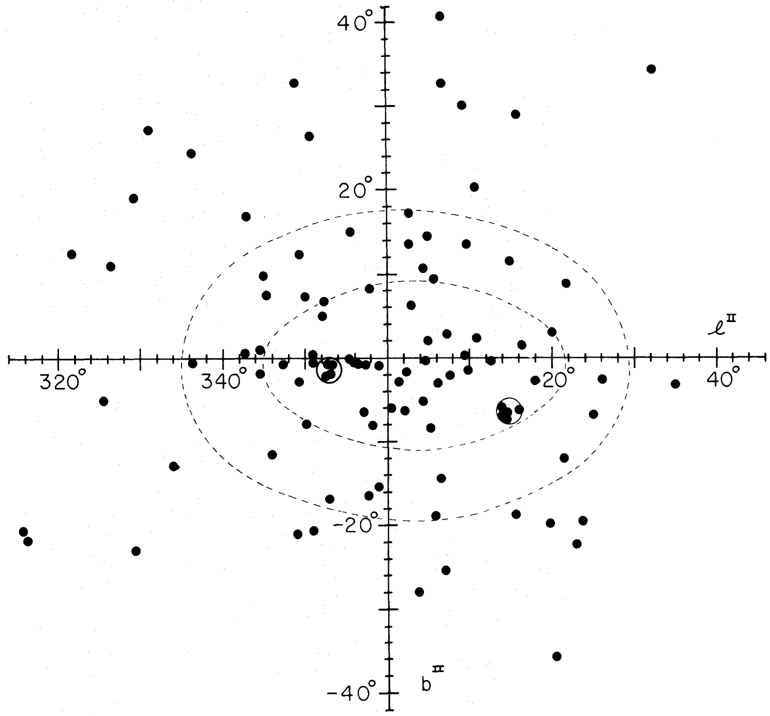

FIG. 5.—Galactic map of arrival directions of 98 γ-rays as obtained from emulsion measurements for the period when the galactic center was in the field of view. The rms uncertainty in direction is shown by the open circles. Regions contained within the dashed curves had relative exposures greater than 75 and 50%.

about $6 \times 10^{-5}\,\gamma\,\text{cm}^{-2}\,\text{s}^{-1}$ (>15 MeV) for an assumed E^{-1} integral spectrum.

There is one other region shown on the map with an anomalously large number of events within the resolution of the telescope. Five events are observed from a region near $l^{II} = 15°$ and $b^{II} = -7°$, whereas the average number expected is only 0.3. Although the evidence is suggestive, we feel that more data are needed to establish the existence of a point γ-ray source at this location.

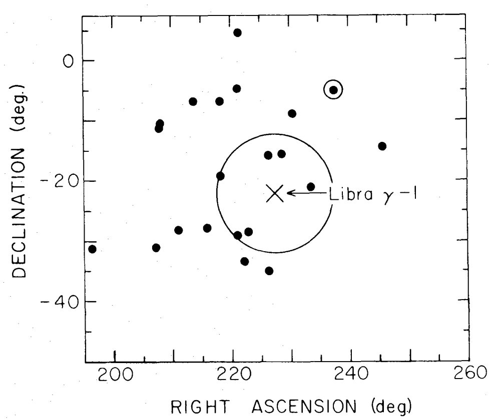

FIG. 6.—Celestial map of arrival directions of 21 γ-rays as obtained from emulsion measurements for the period when Libra γ-1 was in the field of view. The rms uncertainty in direction is shown by the small open circle.

A map of the arrival directions of incident γ-rays observed during the two-hour exposure to the vicinity of the reported variable γ-ray source Libra γ-1 is shown in figure 6. The 21 directions shown were obtained in the emulsion for electron-pair events which were estimated from spark-chamber measurements to have come from within 10° of the reported source (*large circle*). There is no apparent concentration of events near the reported location of Libra γ-1.

IV. DISCUSSION

a) Gamma-Radiation from the Galactic Plane

Our observation of an excess of events from a narrow band along the galactic equator, displayed in figure 4, confirms the detection by Clark *et al.* (1968) of γ-radiation from the galactic plane. Because our measurement was made at energies considerably below those of previous experiments, a comparison of the observed intensities can provide a test of the different production mechanisms suggested for the γ-rays emitted from the region near the galactic center.

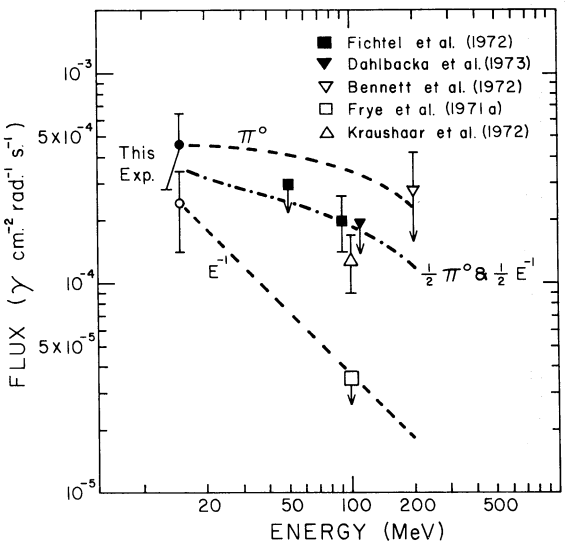

FIG. 7.—Measurements of the flux of γ-rays from the galactic plane near the center of the Galaxy. Our results for assumed π^0-decay (*filled circle*) and power-law (*open circle*) spectra are extrapolated to higher energies (*dashed curves*). Extrapolation of a combined spectrum is given by the dot-dash curve.

Shown in figure 7 are the measured "equivalent line" intensities from this region. As we have discussed earlier, because of the design of our telescope our estimated flux above 15 MeV for an assumed π^0-decay spectrum is significantly higher than our estimated flux for an assumed E^{-1} integral power-law spectrum. These fluxes are plotted separately and are extrapolated to higher energies by the dashed lines following the shapes of the assumed spectra. Shown at 100 MeV are the observed intensities reported by Kraushaar *et al.* (1972) and Fichtel *et al.* (1972), as well as the upper limits reported by Frye *et al.* (1971*a*) and Dahlbacka *et al.* (1973). Bennett *et al.* (1972) have reported marginal evidence for γ-ray emission above 200 MeV; we have therefore treated their quoted intensity as an upper limit. Also shown is an upper limit to the flux emitted between 50 and 100 MeV determined by Fichtel *et al.*

Due to the relatively large "known" uncertainties in the measured fluxes, it is difficult to unambiguously determine the spectrum of γ-radiation emitted from the plane. It is clear, however, that with the exception of the upper limit determined by Frye *et al.*, which is considerably below the other observations (assuming emission from a narrow band), the data are inconsistent with a spectrum as steep as an E^{-1} power law. On the other hand, a π^0 spectrum is not inconsistent with the observations when account is taken of the uncertainties. A better fit to the data is obtained with a composite spectrum consisting of equal contributions from the π^0-decay and power-law processes above 15 MeV.

Recently Helmken and Hoffman (1973) have observed the galactic region with a detector having an angular resolution of about 25° FWHM. They report an excess of emission from the direction of the galactic center, which, if interpreted as diffuse emission from the galactic plane, represents an estimated intensity above 15 MeV of about $10^{-3}\,\gamma\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{rad}^{-1}$. This flux is at least a factor of 2 above the intensities determined in the present investigation and implies a much steeper spectrum. This conflicts with some evidence that we have obtained from measurements of the energies of γ-rays located in the emulsion. We have found that the energy spectrum of γ-rays observed to arrive from within $\pm 3°$ of the galactic equator is at least as "hard" as the spectrum of atmospheric γ-rays over Argentina. In a paper currently in preparation (see also Seeman, Share, and Kinzer 1973), we show that the atmospheric spectrum at this latitude is dominated by a peak at about 70 MeV due to π^0-decay photons. We estimate that these π^0 photons contribute at least 70 percent to the atmospheric γ-ray flux above 15 MeV. The remaining photons follow a steep energy spectrum and are probably bremsstrahlung produced by reentrant albedo and secondary atmospheric electrons.

Anand and Stephens (1972) have recently studied the different mechanisms that are effective in producing γ-radiation from along the galactic plane in the direction of the galactic center. They have considered (1) neutral-pion decay, (2) bremsstrahlung, (3) inverse Compton scattering from the universal blackbody radiation, and (4) inverse Compton scattering from the reported submillimeter radiation (Shivanandan, Houck, and Harwit 1968). The existence of the submillimeter radiation has been broadly questioned by other researchers (see, e.g., Williamson *et al.* 1973); in addition, Anand and Stephens find that its presence leads to inconsistencies with the observations made by Kraushaar *et al.* (1972) from OSO-3 (see also Cowsik 1972). Of the remaining three production mechanisms, we have estimated from figure 6 of Anand and Stephens that about two-thirds of the γ-rays emitted from the plane above about 15 MeV come from π^0 decays. This is in reasonable agreement with our results shown here in figure 7.

The absolute intensity above 15 MeV estimated by Anand and Stephens is considerably below our observed flux. Excluding the contribution from the submillimeter radiation, our observed flux from the plane in the direction of the galactic center is at least a factor of 4 above their calculations (again taken from fig. 6 of their paper). As they remark, this discrepancy between the observations and their calculations indicates that either the cosmic-ray flux and/or the matter density is greater toward the galactic center than is estimated, or there exist point sources of γ-radiation near the center.

Strong, Wdowczyk, and Wolfendale (1973) have suggested that the increased γ-ray intensity toward the galactic center may be due to an increased cosmic-ray intensity in that direction (see also Ginzburg and Khazan 1972). They obtained good agreement with the γ-ray observations of the galactic plane made from OSO-3 for longitudes $l^{II} \approx 13°$ and $l^{II} \approx 227°$, assuming that the cosmic-ray flux is proportional to the galactic magnetic field strength. Their calculations suggest that, near the galactic center ($l^{II} \approx 13°$), the emitted radiation from the plane may be concentrated in a narrow band about 2° wide. This is in agreement with our observations shown in figure 4.

Cowsik and Hutcheon (1971) have suggested that the increase in the observed γ-ray intensity toward the center is due to Compton scattering of starlight by cosmic-ray electrons. Their conclusions are based on the assumption that the density of starlight increases proportionally to the matter density. This would lead to a narrow distribution of γ-radiation from along the plane, which is consistent with our observations. If their estimates are correct, these Compton photons contribute about 70 percent of the observed flux above 100 MeV from the plane in the direction of the center. However, this would produce a relatively soft energy spectrum which appears to be inconsistent with our observations.

We have noted earlier, from the map of γ-ray directions shown in figure 5, that there is a concentration of events within this band for $350° < l^{II} < 360°$. In addition to the presence of point sources, another possible physical explanation for this concentration is based on the observed distribution of atomic hydrogen in the Galaxy. Garmire and Kraushaar (1965) have summarized the 21-cm measurements which reflect this distribution. The map shown in figure 1 of their paper exhibits a high columnar density of atomic hydrogen over an approximately 3°-wide range in latitude for the longitude interval $320° < l^{I} < 330°$. Transformed to new galactic coordinates, l^{II} and b^{II}, this corresponds to the same region in which we observe a concentration of γ-rays. This suggests a possible origin for these γ-rays in cosmic-ray collisions on interstellar gas.

b) *Possible "Point" Sources of Gamma Rays*

In an attempt to explain the observed increase of γ-radiation in the direction of the galactic center, Stecher and Stecker (1970) suggested as a possible source, γ-rays produced from "inverse" Compton scattering of cosmic-ray electrons on the 100-μ radiation observed by Hoffmann, Frederick, and Emery (1971). This infrared emission appears to have an extent somewhat greater than $3.^{\circ}6$ (l^{II}) $\times$ 2° (b^{II}) about the galactic center; therefore, according to the model, we should have observed a very strong γ-ray source within about 2° of the galactic center. Looking at figure 5, we note that there is only one event within 2° of the center. This places an upper limit at the 95 percent confidence level (Hearn 1969) on the flux above 15 MeV of $6 \times 10^{-5}\ \gamma\ \text{cm}^{-2}\ \text{s}^{-1}$.

Detailed calculations of the expected γ-ray intensity from this region near the galactic center have recently been performed by Maraschi and Treves (1972) and Anand and Stephens (1972). The flux above 100 MeV estimated by Maraschi and Treves for the "inverse" Compton process was $3.2 \times 10^{-5}\ \gamma\ \text{cm}^{-2}\ \text{s}^{-1}$; this corresponds to an integral flux of about $2 \times 10^{-4}\ \gamma\ \text{cm}^{-2}\ \text{s}^{-1}$ above 15 MeV, which is a factor of 3 above our upper limit. In their calculations, they assumed that the magnetic field strength in the region was 3×10^{-6} gauss. This field strength requires a cosmic-ray electron intensity about 3×10^{3} times the intensity observed near the Earth in order to reproduce the observed radio emission near the galactic center. A field strength of at least 8×10^{-6} gauss would be required so that the electron intensity can be reduced sufficiently to produce a γ-ray flux above 15 MeV consistent with our upper limit from the galactic center and yet still be consistent with the observed radio emission.

The calculation of the expected flux from the center by Anand and Stephens also includes contributions due to Compton scattering from optical, submillimeter and infrared sources, bremsstrahlung, and π^0 production. They have adopted a magnetic field intensity of about 25×10^{-6} gauss. The integral flux of γ-rays above 15 MeV which they obtain from the galactic center (excluding the contribution from the questionable submillimeter source) is about $3 \times 10^{-5}\ \gamma\ \text{cm}^{-2}\ \text{s}^{-1}$, consistent with our upper limit.

Several point sources of γ-radiation have been reported in the direction of the galactic center (Frye *et al.* 1971*a*, *b*; Browning *et al.* 1972; Dahlbacka *et al.* 1973). These sources were observed at energies above 100 MeV and have estimated fluxes near $2 \times 10^{-5}\ \gamma\ \text{cm}^{-2}\ \text{s}^{-1}$. We have listed the galactic coordinates of these sources in table 1 along with the reported intensities. Comparing these coordinates with our γ-ray maps shown in figures 5 and 6, we find no evidence for an unusual concentration of events near any of the possible sources. Upper limits (95% confidence level) to the integral fluxes from these sources above 15 MeV are given in the table, assuming integral photon spectra $\propto E^{-1}$. Also given in the table are the corresponding upper limits above 10 MeV obtained from our broad resolution survey at about 10° using data obtained from spark-chamber measurements alone. A comparison of our limits at these lower energies with the reported intensities above 100 MeV leads us to conclude that if the sources are real, they must either be variable or their emission spectra must be considerably harder than the E^{-1} power law assumed (e.g., a π^0-decay spectrum).

Frye *et al.* have suggested that the source Gγ 2 + 3 may be associated with the variable hard X-ray source GX 1+4 (2U 1728−24), the spectrum of which has been recently studied by Ricker *et al.* (1973). They have found that the shape of the spectrum, up to about 60 keV, is in agreement with the spectrum of photons up to 500 keV observed from the direction of the galactic center by Johnson, Harnden, and Haymes (1972) with a detector having an aperture of about 25°. This led Ricker *et al.* "to believe that a significant contribution to the X-ray flux measured by Johnson *et al.* came from GX 1+4." From these arguments then, Gγ 2+3, GX 1+4, and the source observed by Johnson *et al.* could all be the same object. However, an extrapolation of the spectrum measured by Johnson *et al.* to higher energies yields a flux about an order of magnitude below the reported intensity of Gγ 2+3.

The source designated by Frye *et al.* (1971*b*) as Libra γ-1 was detected by them at a significance of 6 σ during one balloon flight. However, in a previous flight they found no evidence for it and were only able to place an upper limit on its intensity. This led them to conclude that the source is variable. It is in close proximity to the variable object PKS 1514−24, prompting its tentative identification with this object.

The three sources reported by Browning *et al.* and listed in table 1 were detected with a reported statistical significance of 3.0–3.6 σ. They have been tentatively identified with X-ray sources observed by the *Uhuru* satellite. The authors also suggest that these sources can account for the apparent diffuse emission from the galactic plane. We note, however, that the reality of these sources has been recently criticized on statistical grounds (O'Mongain 1973).

The possible source reported by Dahlbacka *et al.* (1973), although only observed at a 95 percent confidence level, is included in table 1 because it coincides with a region reported by Frye *et al.* (1972) to have an excess of emission. We have found no evidence for emission from this region at energies above 15 MeV. This does not preclude the possibility that there is a source which emits γ-rays with a hard spectrum (e.g., π^0 decay).

The binary X-ray source 2U 1700−37 ($l^{\text{II}} = 347\overset{\circ}{.}7$, $b^{\text{II}} = +2\overset{\circ}{.}2$) reported by Jones *et al.* (1973) was in a high-intensity state during our exposure on 1971 December 1. As seen in figure 4, we find no evidence for emission from this source. The 95 percent confidence level upper limit to the intensity above 15 MeV is $6 \times 10^{-5}\ \gamma\ \text{cm}^{-2}\ \text{s}^{-1}$.

Although we have not made an extensive search in the emulsion for γ-rays from three other potential sources—Sco X-1, the Sun, and Jupiter—we can place upper limits on their emission above 10 MeV from our analysis of spark-chamber data. These limits are 2.0×10^{-4}, 3.7×10^{-4}, and $4.5 \times 10^{-4}\ \gamma\ \text{cm}^{-2}\ \text{s}^{-1}$, respectively, for an E^{-1} integral spectrum.

We have searched the literature for X-ray and radio sources near the location $l^{\text{II}} = 15°$ and $b^{\text{II}} = -7°$ (right ascension 280°, declination −20°) where five γ-ray events fell within the 2° resolution of our instrument (see fig. 4). The closest X-ray source is 3U 1832−23 which is 5° away, well outside our estimated uncertainty. However, there is a radio source located within 2° of this γ-ray excess. It is designated MSH 18−114, and was observed at 85 MHz with an intensity of 56 flux units.

V. SUMMARY

1. We confirm the emission of γ-radiation from along the galactic plane in the vicinity of the galactic center. The equivalent line intensity that we measure above 15 MeV is about $3.5 \times 10^{-4}\ \gamma\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{rad}^{-1}$. The width of the observed band of emission is about 3°, which is considerably narrower than has been reported previously. Comparison with measurements of the equivalent line intensity from the plane at energies above 100 MeV indicates that the integral spectrum of the radiation is considerably harder than an E^{-1} power law; it is consistent with a spectrum dominated by π^0-decay γ-rays.

There is some evidence for a concentration of these galactic γ-rays in the longitude range between $350° < l^{\text{II}} < 360°$. Limited statistics prevent us from determining whether this concentration is due to some point sources in this region. However, radio observations at 21 cm also indicate an increase in the columnar density of atomic hydrogen in this direction.

2. We have placed an upper limit of $6 \times 10^{-5}\ \gamma\ \text{cm}^{-2}\ \text{s}^{-1}$ above 15 MeV on the flux expected from inverse Compton collision of cosmic-ray electrons on the 100-μ radiation observed at the galactic center. This limit suggests that the magnetic field in this region is greater than about 10^{-5} gauss.

3. We have not been able to confirm the existence of any of the previously reported point sources observed above 100 MeV. This suggests that if any of the sources are real, either they must be variable or their spectra are considerably harder than an E^{-2} differential power law, e.g., a π^0-decay spectrum.

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