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EXPERIMENTS IN X-RAY AND GAMMA-RAY ASTRONOMY

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Introduction

We describe here a NASA-supported experimental program which has as its objective the search for cosmic photons in the general range of about 10 kev to 5 Mev. This program uses both balloons and satellites as vehicles; experiments on balloons provide background information, detector studies and hopefully observations of certain specific objects. The major observations are provided by satellite-borne instruments.

Interest in these observations had its origin during my graduate years at Minnesota, under the direction of Dr. J. R. Winckler. During the International Geophysical Year we observed several cases of x-ray bursts from the sun during solar flares. Studies of these events provided considerable new information on solar flares, and caused one to speculate on other possible sources of a stellar or galactic nature. About the same time evidence from optical and radio astronomy caused astrophysicists to predict detectable fluxes of x-rays and gamma-rays at the earth from various celestial objects. This program was started at Minnesota about 1960 and is continuing at La Jolla, where I have been located since 1962.

OSO-1 Experiment

After a few preliminary balloon measurements of the gross features of the cosmic-ray [redacted] exploratory experiment was proposed for the first Orbiting Solar Observatory. This experiment was designed to provide broad energy and angular resolution for non-solar gamma-rays, to monitor the sun for solar bursts, and to provide information on the general background. The experiment covered the 50 kev to about 3 Mev region of the spectrum.

A functional diagram of the instrument is shown in Figure 1. A simple NaI scintillation counter with a lead pipe collimator provides a directional detector in the 50 to 150-kev range. At higher energies, lead collimators are known to produce more gamma-ray background from cosmic rays than they attenuate so a device known as a Compton telescope was used. This device uses two scintillation counters in coincidence. By placing a requirement on the energy of an electron scattered by an incoming photon, one obtains a device which has a directional response to gamma-rays. As designed for the OSO-1 satellite, the Compton telescope had a response of about 12° half-angle for Co^{60} gamma-rays, a rejection factor of about 30 at large angles and a forward efficiency less than 1%. The total isotropic gamma-ray flux was measured with the absorbing counter of the Compton telescope, which was a 2" x $2\frac{1}{2}$" NaI counter of the phoswich type. This type of counter rejects edge effects due to charged cosmic-rays and other particles. In addition, overall isotropic and coincidence rates were monitored to provide a measure of cosmic-ray effects. These rates were monitored when the satellite was in a night mode and direction references, required for operating the telescopes, were not available.

The instrument, shown in Figure 2, was designed to fit in the wheel compartment of an OSO satellite. The instrument weighed about 30 pounds, had about 400 transistors in it and required about 0.5 watt of power.

[redacted]

The entire instrument was designed, constructed and tested in the laboratories and shops of the University of Minnesota.

Since not everyone is familar with the OSO series of NASA satellites, a brief description is in order. A photo of the first OSO is shown in Figure 3. An OSO consists of three basic structures: a wheel section which rotates at about 0.5 rps, and provides a stiff axis for torquing against. The wheel axis is servoed to lie a plane perpendicular to the earth-sun line. A directional experiment, placed in a compartment of an OSO and looking radially outward, sweeps the sun, the sky, and most likely the earth below every two seconds. The second portion of the OSO is the sail structure, which contains the solar cell power plant. This is servoed in azimuth to point to about 1 minute of arc to the sun. The third, or pointed section, is servoed in elevation, also to about 1 minute of arc. Instruments, such as x-ray or L_α telescopes or spectrometers may be placed in this section, and point at a given spot on the sun with great accuracy. In addition, of course, the satellite is provided with the needed control, command, and data handling facilities. An on-board tape recorder provides nearly continuous information retrieval.

The OSO-1 was launched March 7, 1962 into a near circular 550-Km orbit of 33° inclination and 95-minute period. Inspection of the data indicated that the cosmic-ray background effects were considerably greater than anticipated, and that in addition, certain completely unanticipated effects were observed. Reduction of about 500 quasi-analog magnetic tapes, and combining the data with orbit parameters was, of course, found to be a non-trivial problem, and is just now being finished in a completely satisfactory manner. In the meantime, the physical effects have been understood, even though all of the data has not been run through the computer for the last time.

Two of the important effects are indicated in Figure 4, where we show the rates of the isotropic gamma-ray counter as the satellite crossed a meridian of longitude, 60° E. The lower branches of the curves are due to cosmic-ray production in the satellite and in the earth below; the upper branches were found due to radioactivity induced in the NaI detector during the brief passages of the satellite through the trapped radiation over the South Atlantic region. Neutrons, produced by trapped protons, are captured by the I^{127} of the detectors to form I^{128}, which β-decays with a 25-minute half-life. This result, in addition to complicating analysis of the OSO-1 data, has influenced planning on future missions.

Of course, the most important objective was the search for the extraterrestrial flux. In Figure 5 we show the upper limits from this experiment. These limits were obtained from the total counting rate of the isotropic counters over the geomagnetic equator, correcting for a gain change of the detectors and selecting passes where induced radioactivity was not important. Presumably cosmic ray effects are minimized in this manner; however as indicated in Figure 4, they are not zero. An extra-terrestrial flux, would, of course, be latitude independent. Also shown are the fluxes actually measured by Arnold and his collaborators on the Ranger III, with an isotropic counter on a boom, half-way between the earth and the moon. The two measurements can just be reconciled. The lowest energy point of the OSO-1 upper limits is not in disagreement with those measured by Arnold; the solid angle of the lead pipe detector on the OSO-1 is considerably less than 4π. These fluxes are of course the total, from all sources, both point and diffuse, integrated over 4π solid angle.

Balloon Studies

About the time of launch of the OSO-1, it became apparent that knowledge of the cosmic-ray produced gamma-ray fluxes was inadequate to intelligently plan and design experiments for cosmic photon measurements in this general energy range. Accordingly, a series of balloon investigations were undertaken. A balloon-borne gamma-ray detector above about 110,000 feet is essentially exposed to the same cosmic-ray composition and intensity it will find on a satellite or in space; however, because of interactions in the atmosphere, the gamma-ray background is somewhat worse. The balloon investigations then have two purposes, one to increase basic knowledge of cosmic-ray processes in the atmosphere. This may, of course, shed light on processes on a galactic or cosmic scale. The second purpose is to actually test designs of instruments for x-ray and gamma-ray astronomy. In addition, recent evidence indicates it is possible to observe certain celestial objects from balloons in the light of their x-rays.

One of the early objectives was to interpret the OSO-1 results, particularly in respect to the effects of local matter near the scintillation detectors. Accordingly, a number of balloon flights were accomplished. The detectors of a backup instrument were first flown with local instrument matter, such as circuits, magnesium housings, and lead collimators present in the OSO-1 flight configuration. Then this matter was removed, and detectors placed, with their geometry preserved, in a styrofoam block. Some of the results of this study are shown in Figure 6. About 20% or so of the single counter rates on the OSO-1 can be attributed to production in the instrument materials. Rates which involved scintillation counters in coincidence decreased a factor of ten or so when the instrumental material was removed.

Some of the general features of gamma-ray intensities on the earth, in the atmosphere and in space are also indicated in Figure 6. The rates at sea level are due to radioactivity in the rocks and soils; as soon as the balloon leaves the ground the intensity drops a factor of ten or so, then increases with the atmospheric cosmic-ray intensity and goes through a transition maximum with the charged cosmic-ray component. At high altitude, the gamma-ray intensity is comparable to that at sea level. The flux in space is apparently several factors below that measured at 110,000 feet on a balloon, and much less than that due to local radioactivity of the rocks and soils.

Other measurements have provided information of a more fundamental nature. Figure 7 shows the spectrum at 110,000 feet between about 40 and 700 kev obtained with a NaI crystal and a 16 channel pulse spectrum analyzer. The gamma-ray line at 0.5 Mev was first measured in the atmosphere in these experiments. This line is due to positrons, produced by cosmic-ray interactions, stopping and annihilating in the atmosphere.

The exact source of the atmosphere gamma-rays at low energy; that is whether they are produced by electromagnetic process from the soft component of cosmic rays or by low energy nuclear interactions on atmospheric nuclei, can be determined from the shape of the spectrum between 1 and 10 Mev. Figure 8 shows a simple apparatus, built in collaboration with Dan Schwartz, a graduate student at UCSD. It consists simply of a 3"x3" counter with a plastic anticoincidence shield to reject cosmic-rays. The entire apparatus consists of a 128 channel pulse-height analyzer and a telemetry system, and has been flown on balloons twice now. The results of a flight over Yuma, Arizona to 110,000 feet (6 gm/cm^2 atmospheric depth) are shown in Figure 9. The points on the spectrum between 1 and 10 Mev were obtained in this experiment. Although there is some indication of line structure, clearly the most important component of the spectrum is the steep continuum. This is regarded as evidence that the significant source of lower energy gamma-ray is from the degraded products of the soft component. This component has its origin in π^0 mesons produced in the first few radiation lengths from the top of the atmosphere. Gamma-rays produced by nuclear exitation and neutron inelastic scattering and capture, would show a definite line structure and would tend to peak at about 6 or 8 Mev. Also shown are measurements made on other flights, and by other workers, to complete the general picture of low energy gamma-rays in the atmosphere.

The OSO-III Experiment

Another result of the balloon work, in collaboration with Ken Frost of NASA's Goddard Space Flight Center, has been the development of an x-ray detector. This detector operates in the region about 7 kev to 200 kev, and is designed for the third OSO. The general block diagram of the detector is shown in Figure 10. It is similar to the collimated detector flown on the OSO-1, except for the important difference that the collimating shield is constructed of CsI, a scintillating material. The shield is then placed in electrical anti-coincidence with the control detector. In this way, background effects produced by cosmic-rays in the collimator and are removed electrically, and one obtains a shield whose rejection is close to the theoretically predicted response. The experiment is limited by phototube noise on the low energy end, and by the finite shield thickness at high energies.

The instrument as constructed for the OSO-III has eight logarithmically spaced differential channels of pulse-height analysis. There is of course a rather elaborate system of storage, coding, direction indication, subcommutation and signal conditioning associated with the complete instrument. This instrument is, once again, designed to be placed in a wheel compartment of an OSO-looking radially outward. This instrument is on the third OSO, which now scheduled for launch in a few months, during the second quarter of 1965.

A photo of the complete instrument is shown in Figure 11. Since this project started soon after we arrived at La Jolla, and there was insufficient technical support available at the time, the entire instrument design and construction was subcontracted. The name of the subcontractor appears on the instrument, naturally.

This instrument was flown on a balloon during the breadboard phase to determine its background and to verify the properties of the active anti-coincidence collimators. The background determined from this flight, together with present experimental situation on cosmic fluxes is indicated in Figure 12. Shown is the differential photon spectrum from cosmic sources as a function of energy. About a dozen x-ray sources, generally in the direction of the galactic center, have now been identified at energies of a few kilovolts. These observations, some of which are indicated on the figure, have been obtained from rocket flights by the groups at the Naval Research Laboratory, American Science and Engineering, and MIT. Also shown is the flux at about 40 kev measured from the Crab Nebulae from a balloon by George Clark of MIT, and the results obtained from Ranger and the OSO-1 at higher energies. It should be indicated that the rocket and balloon results pertain to single localized point sources, while the results at higher energy include all sources, integrated over the total solid angle.

The measured background of the OSO-III detector for point sources as determined at balloon altitudes is also indicated. Most likely at satellite altitudes the background will be less. Clearly, the experiment will provide new and important observations of cosmic x-rays, and will contribute to our continually accumulating knowledge in a new and exciting area.

NASA-University Relations at UCSD

I am compelled by the nature of the program here to make some remarks of a non-scientific nature. The situation at the University of Minnesota is rather well known, and has been described in some detail in the previous paper by Dr. Winckler.

The San Diego campus of the University of California is fairly new, and was formed from the Scripps Institution of Oceanography about 6 years ago. It received a considerable impetus under the direction of such men as Roger Revelle, Harold Urey, James Arnold and Keith Brueckner. Until this past fall it was only a graduate school. There are now about 400 graduate students. This year 175 freshman undergraduates were admitted. This past year Revelle College, of which we are a part, has begun occupying its new and permanent quarters.

Space related work has been carried on for some time by the geochemists and earth science people at UCSD. I refer to studies of meteorites, cosmic dust, lunar and planetary compositions, etc. under Harold Urey, Jim Arnold, Gustaf Arrhenius and their collaborators. Space physics, as such, in the Physics Department started about three years ago when Carl McIlwain, formerly a student of Van Allen at Iowa, and myself arrived at La Jolla. We arrived at, essentially, six empty rooms. McIlwain, whose present main interest is the trapped radiation, and myself are now located in the same area and between us we occupy most of one floor of one wing of the Physics Department. Also located in the same wing are the plasma physicists, and the astrophysicists, the groups with which we interact the most.

Between McIlwain and myself we now support about 25 people - scientific and technical personnel and graduate students. There is one engineer, a technician, a computer programmer, and about four students working on the gamma-ray astronomy projects. McIlwain and myself each have sustaining grants from NASA headquarters, as well as hardware and data reduction contracts for specific missions from GSFC. We share labs and facilities as much as possible.

UCSD does not have an interdisciplinary grant; one is currently being proposed. In terms of general facilities UCSD has an excellent computer center; the machine shop is about one year old and will become quite good after the shakedown is completed. There is no general electronic facility with high class electronic designers. The electronics are done presently in our own labs.

Our balloon flights at UCSD were formerly handled by the remains of the Convair group at General Dynamics/Astronautics. Their balloon group was closed down last year. We are presently building up to a small in-house balloon facility. Flights involving large balloons are handled through the NCAR facilities at Palestine, Texas.

I wanted to emphasize the relation of the balloon experiments to the program as a whole. The balloon experiments allow a graduate student to do something fairly quickly at the start, and to obtain some results soon. Satellite experiments are admittedly long term projects, and not ideally suited for a graduate student, particularly if followed from experiment conception to final analyses of the data. It seems possible for a student to study the properties of an instrument using balloons, and do some related measurements, then analyze data from a mission which used the instrument for a thesis. Also, it seems possible to work backwards, that is have a student work on data for an initial cut, then do a balloon experiment, or develop a satellite instrument and use it to obtain some important measurement from a balloon. I certainly concur with the previous papers that a student who has only analyzed someone else's data for a thesis has not had a complete education in experimental physics. The use of rockets and balloons in conjunction with satellite experiments adds a considerable degree of flexibility to a graduate space program. Of course, it is not possible to use this combination in every area of research.

Finally, I also wanted to make a few remarks about subcontracting instrument development and construction for space missions, as was done for the OSO-III experiment. Unless one is fairly highly staffed, or has many experienced and eager graduate students, it is very difficult for a single investigator to reduce data from previous missions, teach, and to have some time to think, at the same time he is concerned about delivering hardware for a specific launch. Under such a situation, which was what we faced two years ago, a subcontract for the hardware seems appealing and may even be desirable.

Of course, the investigator must know all the constraints of the experiment well, so that the physical judgements have been made before a subcontractor can start. Even then there is some danger that one after two years of subcontractor effort, one may be delivered a nearly useless box of junk. In order to retain control over the experiment in our case, we were able to make effective use of the PERT system. PERT, which means Performance Evaluation and Review Technique, is a management method which is used on the OSO program by NASA. Constructed into the PERT chart were approval points, at which we had to go to the subcontractor, look at the apparatus, perform calibrations, measurements, observe pulses, or whatever was appropriate. This allowed an impersonal way of indicating to NASA if the apparatus being constructed by the subcontractor was not satisfactory. Fortunately, in our case, every thing was generally all right and relations with the subcontractor were most pleasant; nevertheless, the control existed. It was found about 6 months were required after program approval while NASA, the University and the subcontractor argued about contractual details. During that time we were able to proceed on a limited basis, and although no actual hardware was constructed the time was not completely lost. It would seem that some effort should be made on NASA's part to reduce these times.

Summary

I have tried to present a unified program in x-ray and gamma-ray astronomy, in which balloon experiments are used to support satellite missions. I have tried to indicate something of the instrumental techniques used in these studies, and the present state of knowledge of x-ray astronomy. I have also tried to show how this program fits into the academic program at UCSD as a whole, and, at least in one case, how an investigator uses staff, students and facilities in a NASA-supported scientific program.

Acknowledgements

The author is particularly indebted to Dr. J. R. Winckler for his encouragement during the early phases of this program. These experiments would not have been possible without the loyal support of the author's technical staff, and his students. This research was supported under NASA contract NASw-56 at Minnesota, and grant NsG-318 at La Jolla as well as contracts NAS5-3122 and NAS5-3177 with The Goddard Space Flight Center.

References

Arnold, J. R., E. C. Anderson, A. E. Metzger, M. A. Van Dilla, "Detection of an Interstellar Flux of Gamma-Rays," Nature, 204, 766-767, 1964.

Bowyer, S., S. Byram, T. A. Chubb, H. Friedman, "Cosmic X-Ray Sources," Science, 147, 3656, 394-398, 1965.

Burbidge, G. R., R. J. Gould, "High Energy Cosmic Photons and Neutrinos," Annales D'Astrophysique, 28 (to be published) 1965.

Clark, G. W., "Balloon Observation of the X-Ray Spectrum of the Crab Nebula above 15 KEV," Physical Review Letters, 14, 91-94, 1965.

Giacconi, R., H. Gursky, F. R. Paolini, B. B. Rossi, "Further Evidence for the Existence of Galactic X-Rays," Physical Review Letters 11, 530, 1963.

Hafner, E. M., "Cosmic Electromagnetic Radiation," Science, 145, 1263-1270, 1964.

Hicks, D. B., L. Ried, Jr., L. E. Peterson, "X-Ray Telescope for an Orbiting Solar Observatory," 11th Nuclear Science Symposium, IEEE (to be published Jan. 1965 Transactions PTGNS).

Morrison, P., "On-Gamma-Ray Astronomy," Nuovo Cimento, 7, 858-865, 1958.

Peterson, L. E., and R. L. Howard, "Gamma-Ray Astronomy in Space in the 50-kev to 3-Mev Region, IRE Trans. on Nuc. Sci., NS-8, 4, 1961.

Peterson, L. E., and J. H. Nitardy, "Simple Circuit for a Phoswich Scintillation Counter," Rev. of Sci. Instr. 32, 1390-1392, 1961.

Peterson, L. E., "Radioactivity Induced in NaI by Trapped Protons, Journal of Geophysical Research, 1 Apr. 1965 (In Press).

Peterson, L. E., "The 0.5-Mev Gamma-Ray and the Low-Energy Gamma-Ray Spectrum to 6 Grams Persquare Centimeter over Minneapolis," Jour. of Geophysical Research, 68, 979-987, 1963.

Figure Captions

Figure 1 Block diagram of an exploratory experiment in gamma-ray astronomy designed for the First Orbiting Solar Observatory.

Figure 2 A photograph of the OSO-1 instrument. The instrument weighed about 30 pounds, contained 400 transistors, and drew one-half watt of power.

Figure 3 A photo of the First OSO. The wheel section spins at about one-half rps, with the spin axis constrained to lie in a plane perpendicular to the earth-sun line. The solar cell array is mounted on the sail. Instruments in the pointed section are servoed on the sun to about one arc-minute.

Figure 4 Rates of the isotropic detectors on the OSO-1, as a function of geographic latitude. The lower curves are due to cosmic-ray effects, the upper curves due to induced radioactivity in the counters.

Figure 5 Upper limits of cosmic fluxes from the OSO-1 compared with the measurements of Arnold, et al on the Ranger III.

Figure 6 Total gamma-ray counting rates on the ground and in the atmosphere obtained during a balloon study with the OSO-1 detector. The rates in space are several factors less than those at 6 gm/cm^2.

Figure 7 The gamma-ray spectrum in the atmosphere at 110,000 feet over Minneapolis. The gamma-ray at 0.5 Mev is due to annihilation of cosmic-ray produced positrons.

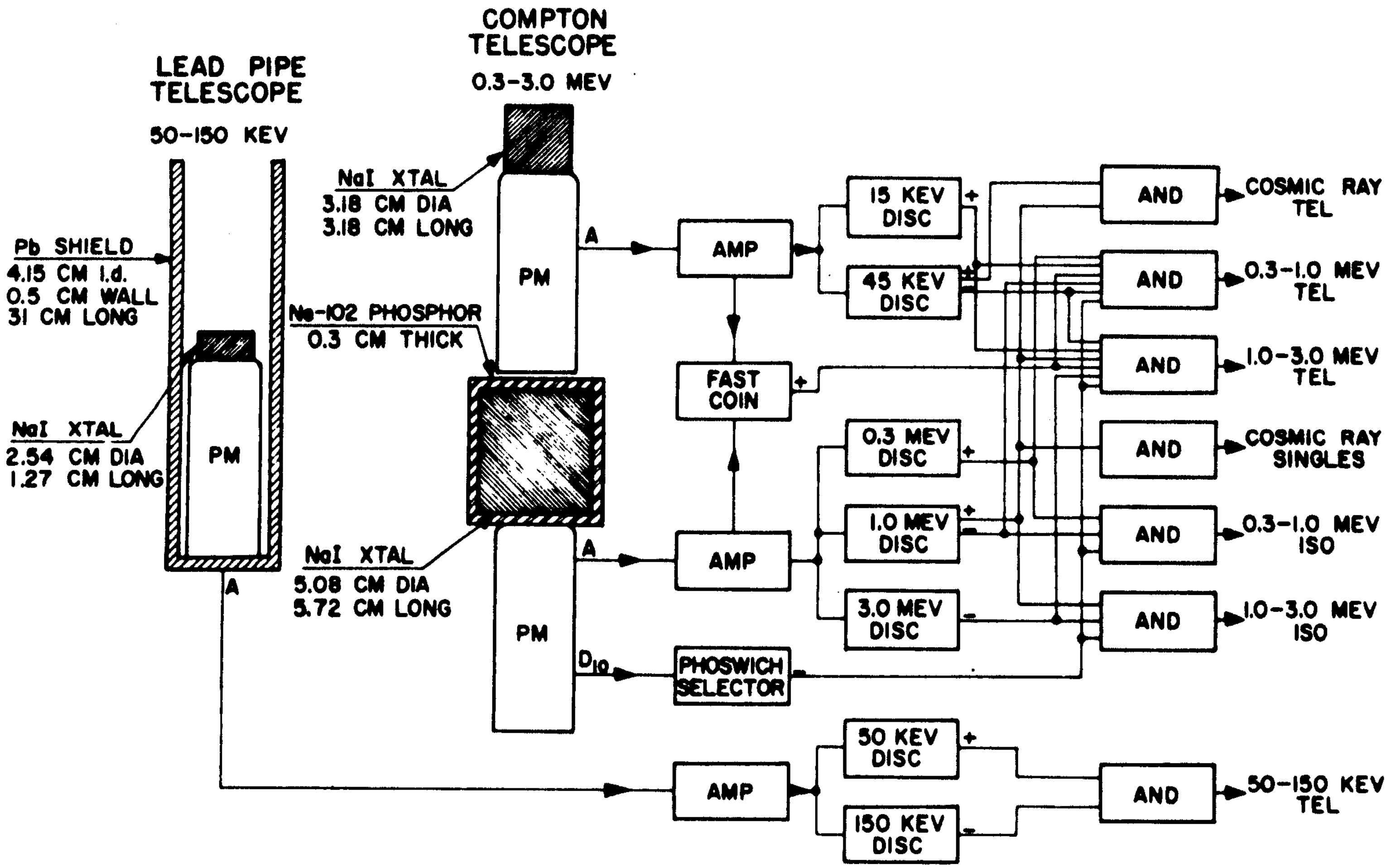
Figure 8 A simple apparatus flown on a balloon to study the gamma-ray spectrum between 1 and 10 Mev.

Figure 9 Various results obtained over Yuma, Arizona. The general steepness of the spectrum and the lack of outstanding line structure between 1 and 10 Mev is taken to indicate most of the atmospheric gamma-rays originate in cascade electromagnetic processes.

Figure 10 The block diagram of an x-ray detector designed for the OSO-III satellite. The active CsI collimator is placed in anti-coincidence with the central detector, giving a very low background count.

Figure 11 A photo of the OSO-III detector. This instrument is also designed to be placed looking radially outward from wheel compartment on OSO satellite.

Figure 12 The differential spectrum of measured cosmic x-ray fluxes. This is compared with the background of the OSO-III detector as measured on a balloon flight. The point sources at low energies were measured on rocket flights. The Crab Nebulae at 40 kev was measured from a balloon. The results at higher energies pertain to the entire 4π solid angle of the sky.



γ-RAY DETECTORS & DETECTOR LOGIC

Figure 1

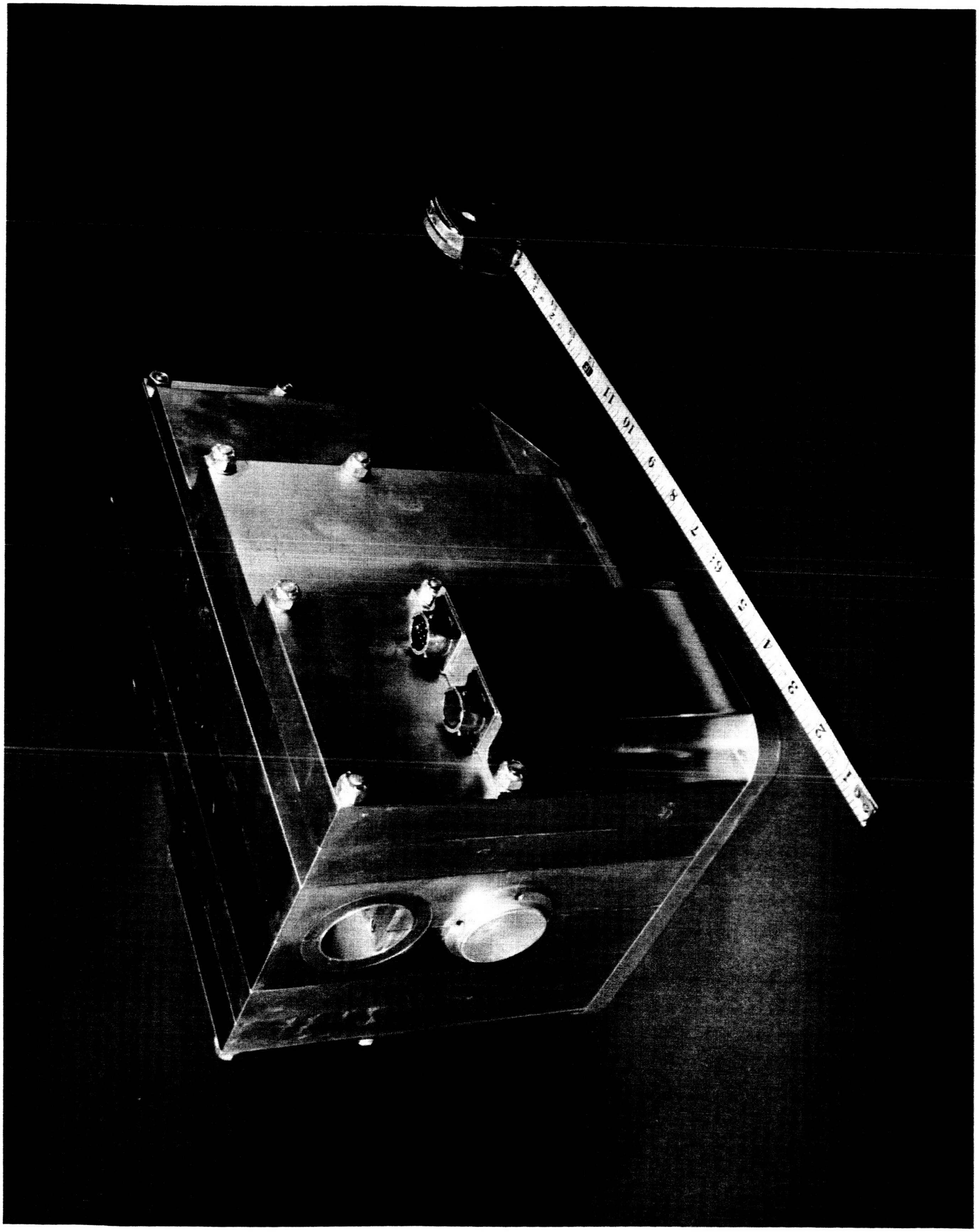
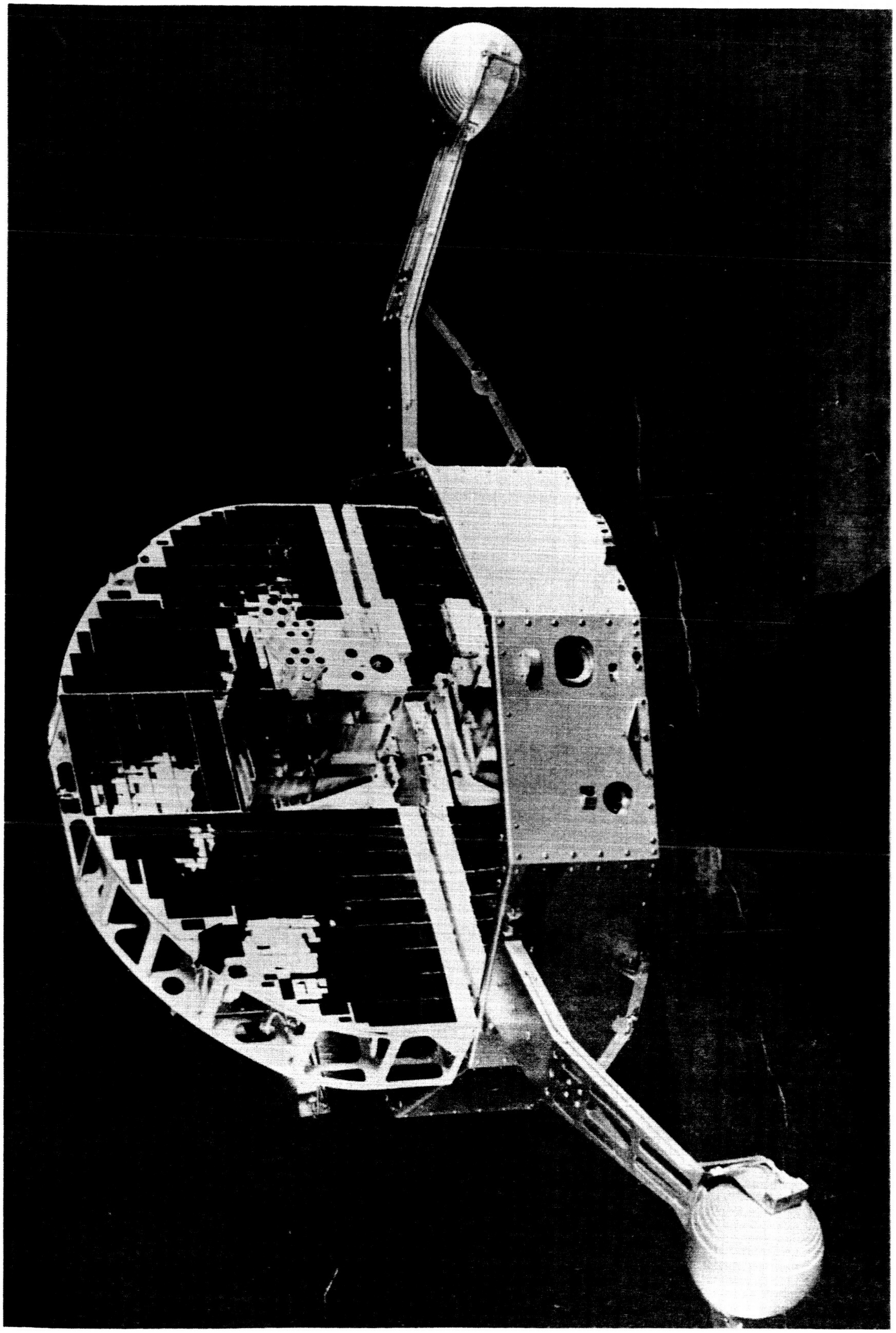


Figure 2



Orbiting Solar Observatory

Figure 3

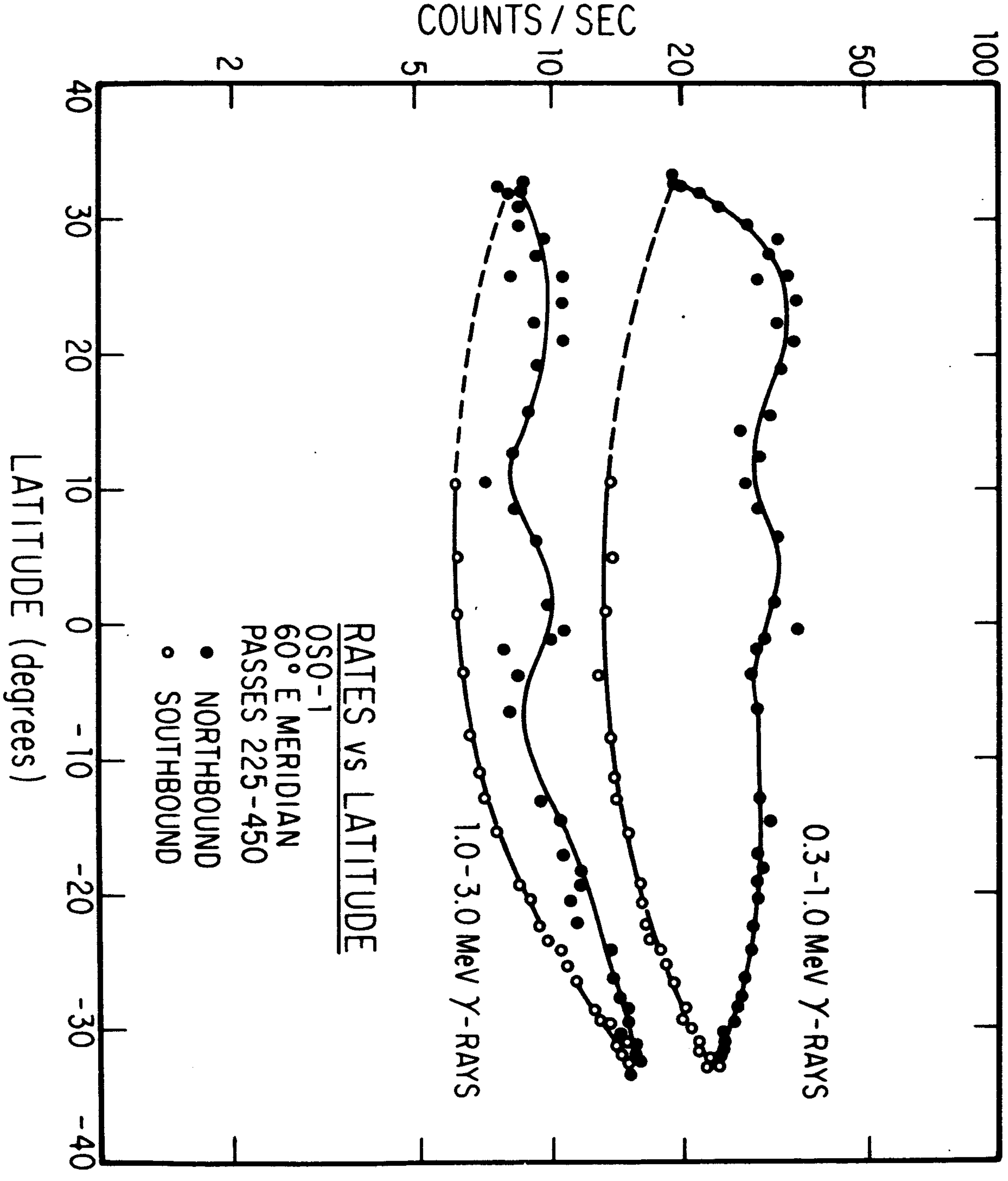

COUNTS / SEC
100
50
20
10
5
2
40
30
20
10
0
-10
-20
-30
-40
LATITUDE (degrees)
0.3-1.0 MeV γ-RAYS
1.0-3.0 MeV γ-RAYS
RATES vs LATITUDE
OSO-1
60° E MERIDIAN
PASSES 225-450
● NORTHBOUND
○ SOUTHBOUND

Figure 4

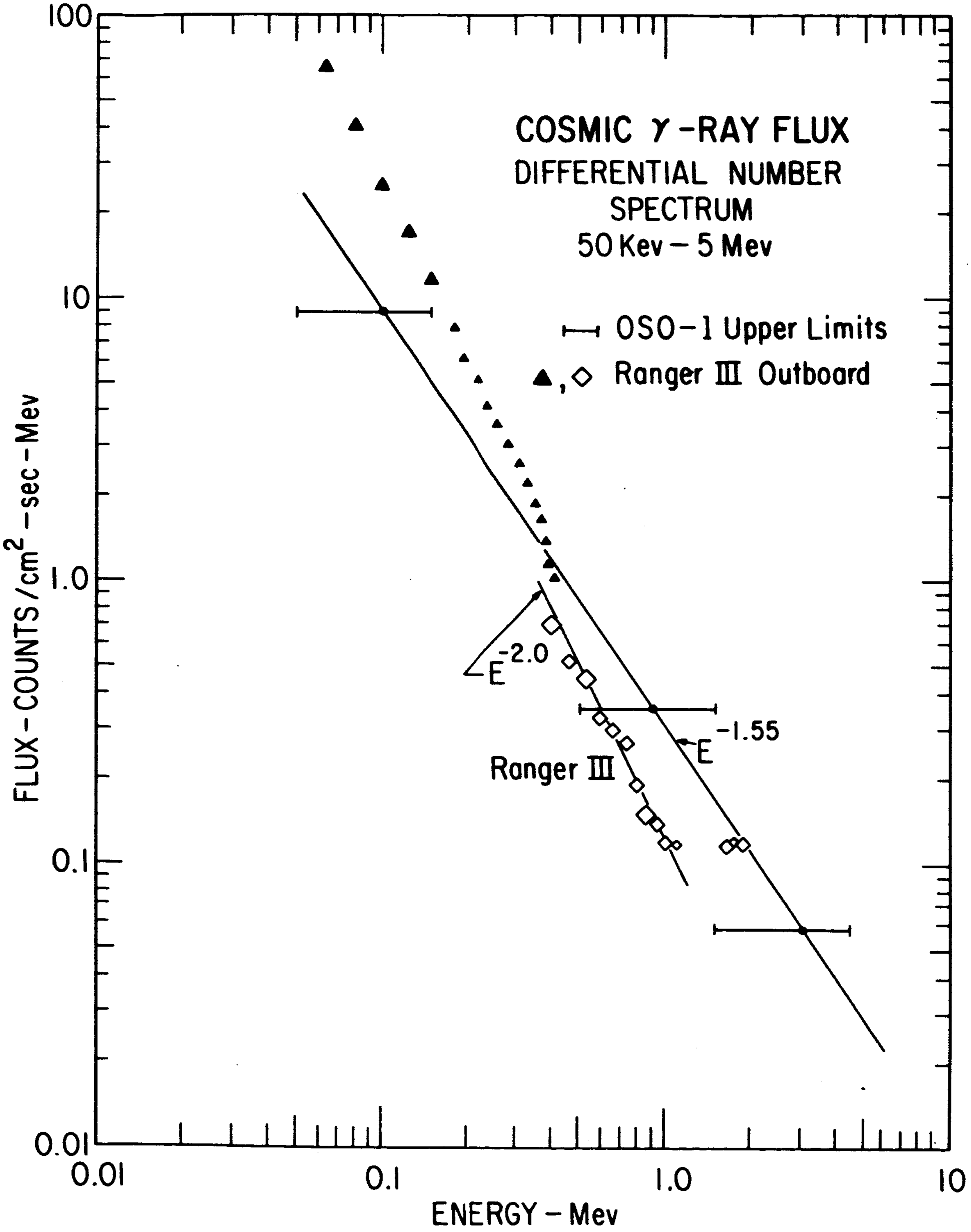

COSMIC γ-RAY FLUX
DIFFERENTIAL NUMBER SPECTRUM
50 Kev – 5 Mev
OSO-1 Upper Limits
▲, ◇ Ranger III Outboard
$E^{-2.0}$
$E^{-1.55}$
Ranger III
FLUX-COUNTS/cm² -sec-Mev
ENERGY – Mev
100
10
1.0
0.1
0.01
0.01
0.1
1.0
10

Figure 5

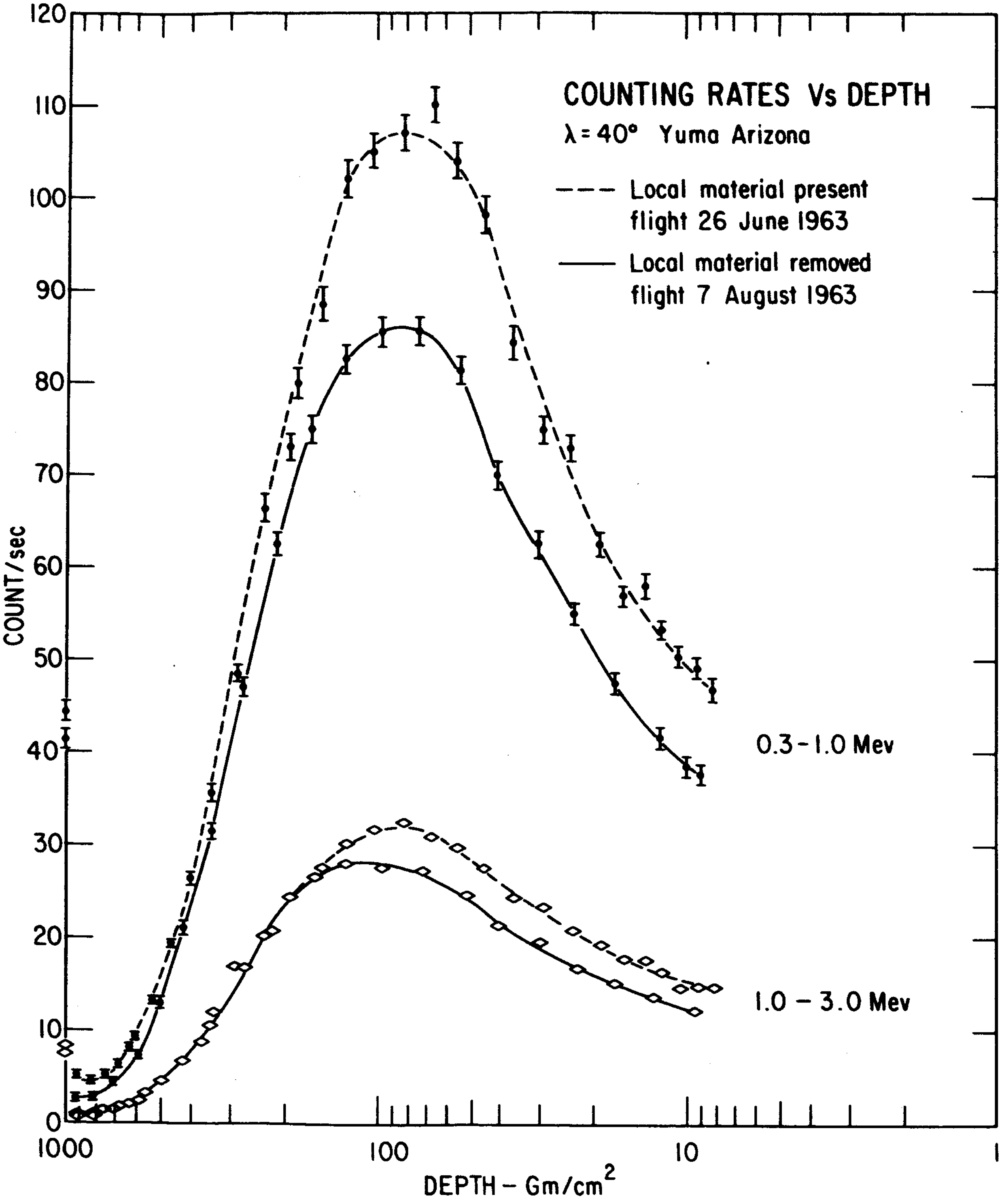

COUNTING RATES Vs DEPTH
λ = 40° Yuma Arizona
Local material present flight 26 June 1963
Local material removed flight 7 August 1963
0.3 - 1.0 Mev
1.0 - 3.0 Mev
COUNT/sec
DEPTH - Gm/cm²
120
110
100
90
80
70
60
50
40
30
20
10
0
1000
100
10
1

Figure 6

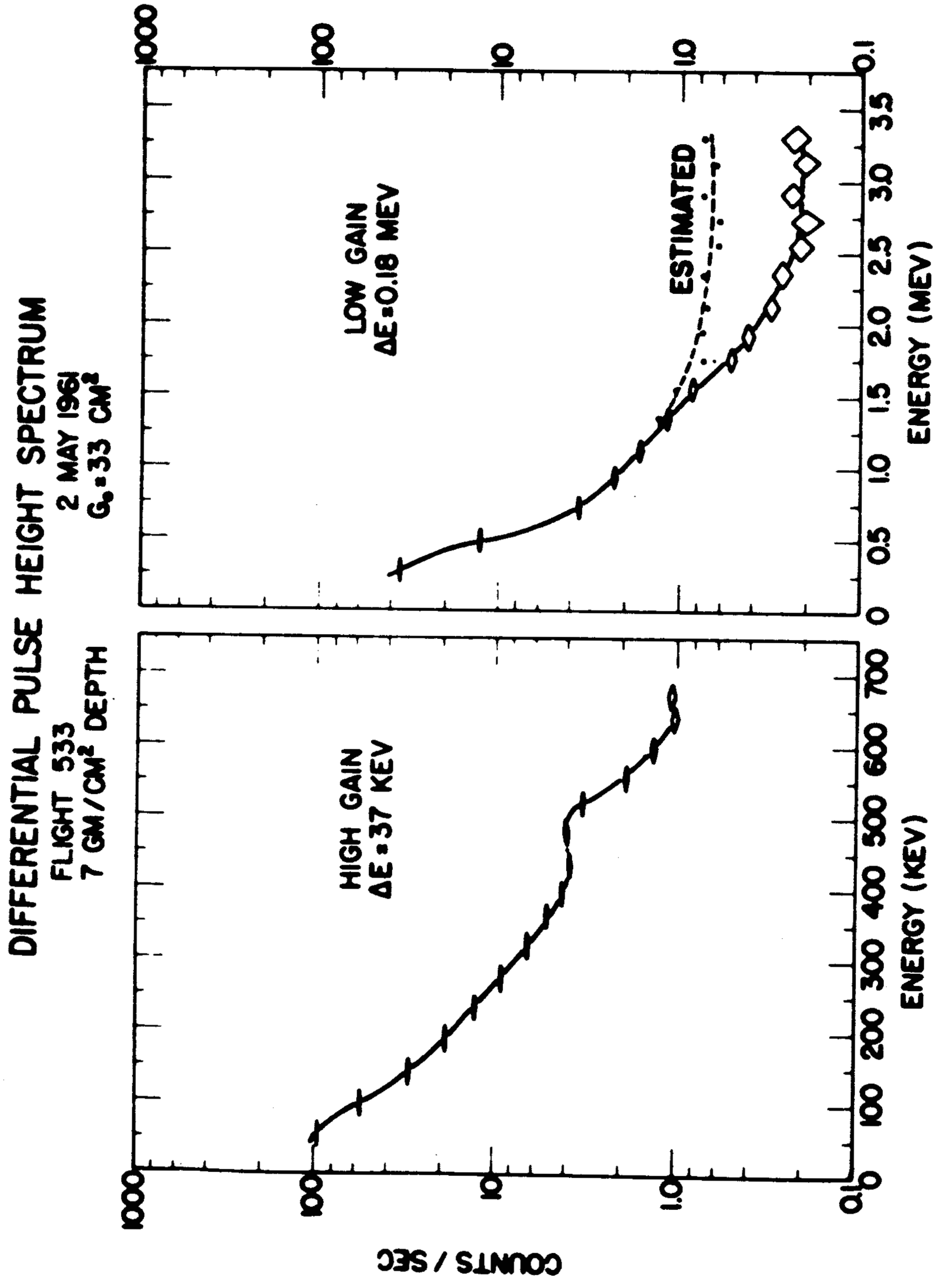

DIFFERENTIAL PULSE HEIGHT SPECTRUM
FLIGHT 533
7 GM/CM² DEPTH
2 MAY 1961
G₀ = 33 CM²
HIGH GAIN
ΔE = 37 KEV
LOW GAIN
ΔE = 0.18 MEV
ESTIMATED
COUNTS / SEC
1000
100
10
1.0
0.1
0
100
200
300
400
500
600
700
ENERGY (KEV)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
ENERGY (MEV)

Figure 7

MEDIUM ENERGY γ-RAY DETECTOR

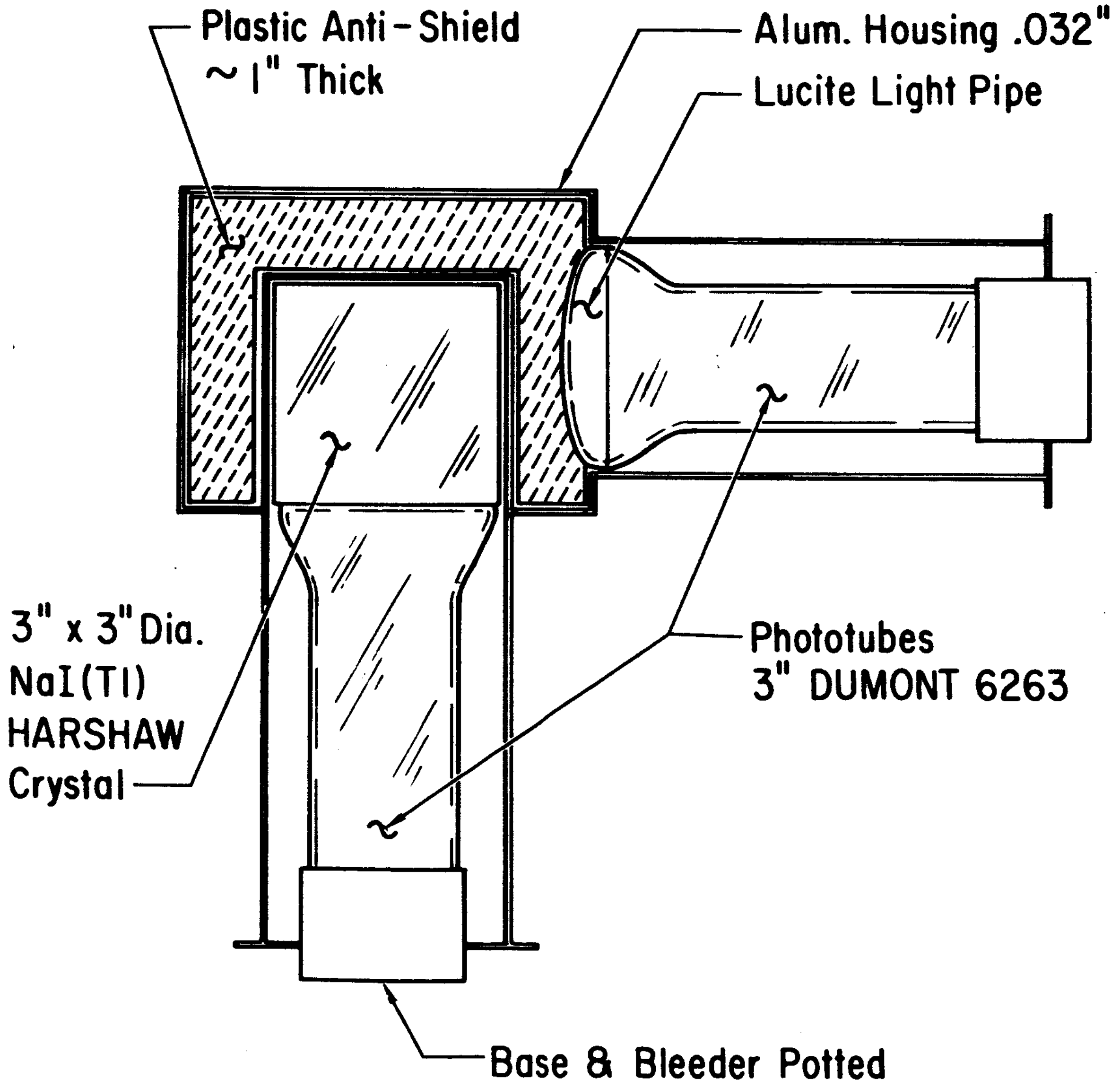


Figure 8

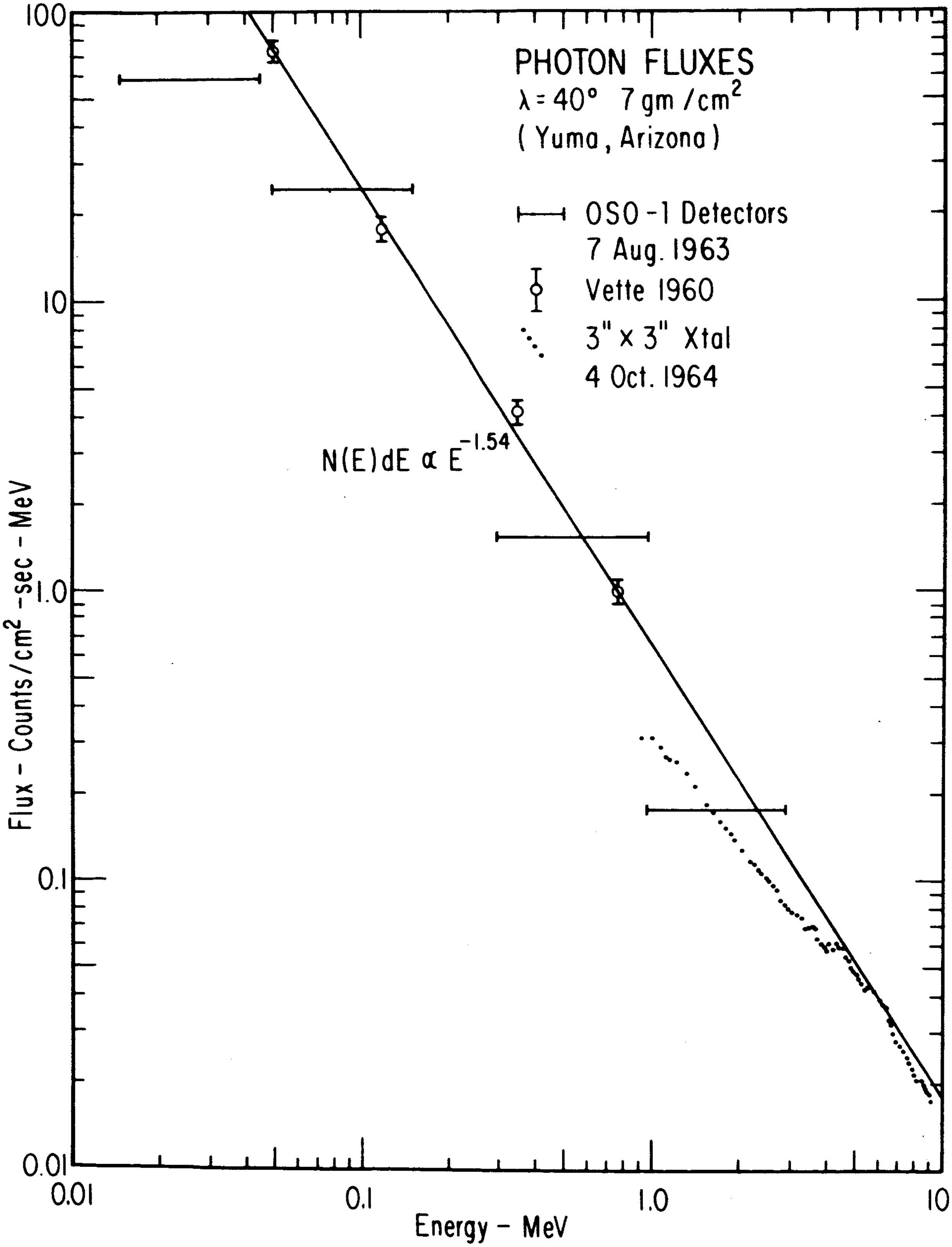
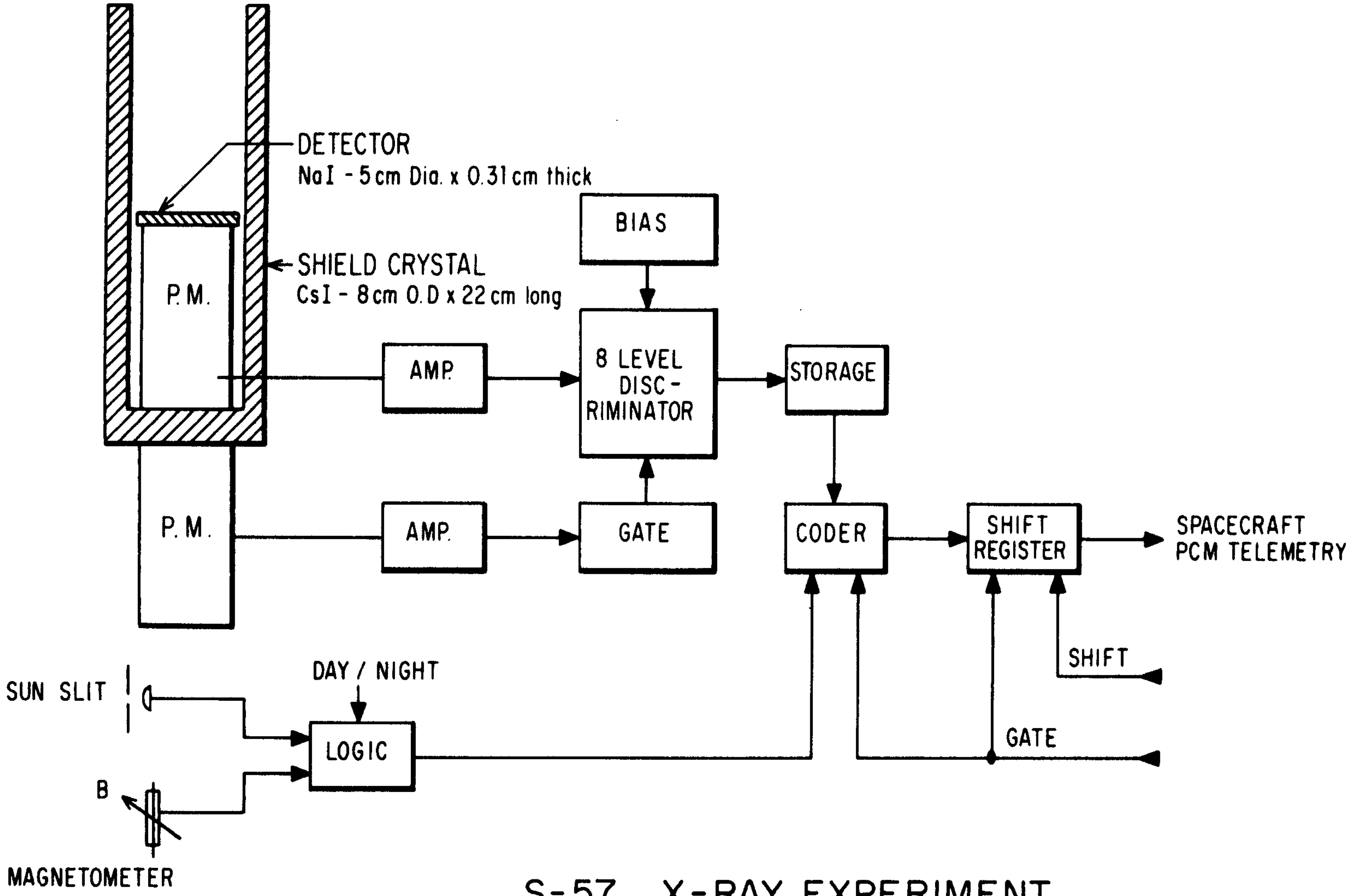

PHOTON FLUXES
λ = 40° 7 gm/cm²
(Yuma, Arizona)
OSO-1 Detectors
7 Aug. 1963
Vette 1960
3" x 3" Xtal
4 Oct. 1964
N(E)dE α E^-1.54
Flux - Counts/cm² -sec - MeV
100
10
1.0
0.1
0.01
0.01
0.1
1.0
10
Energy - MeV

Figure 9



S-57 X-RAY EXPERIMENT

Figure 10

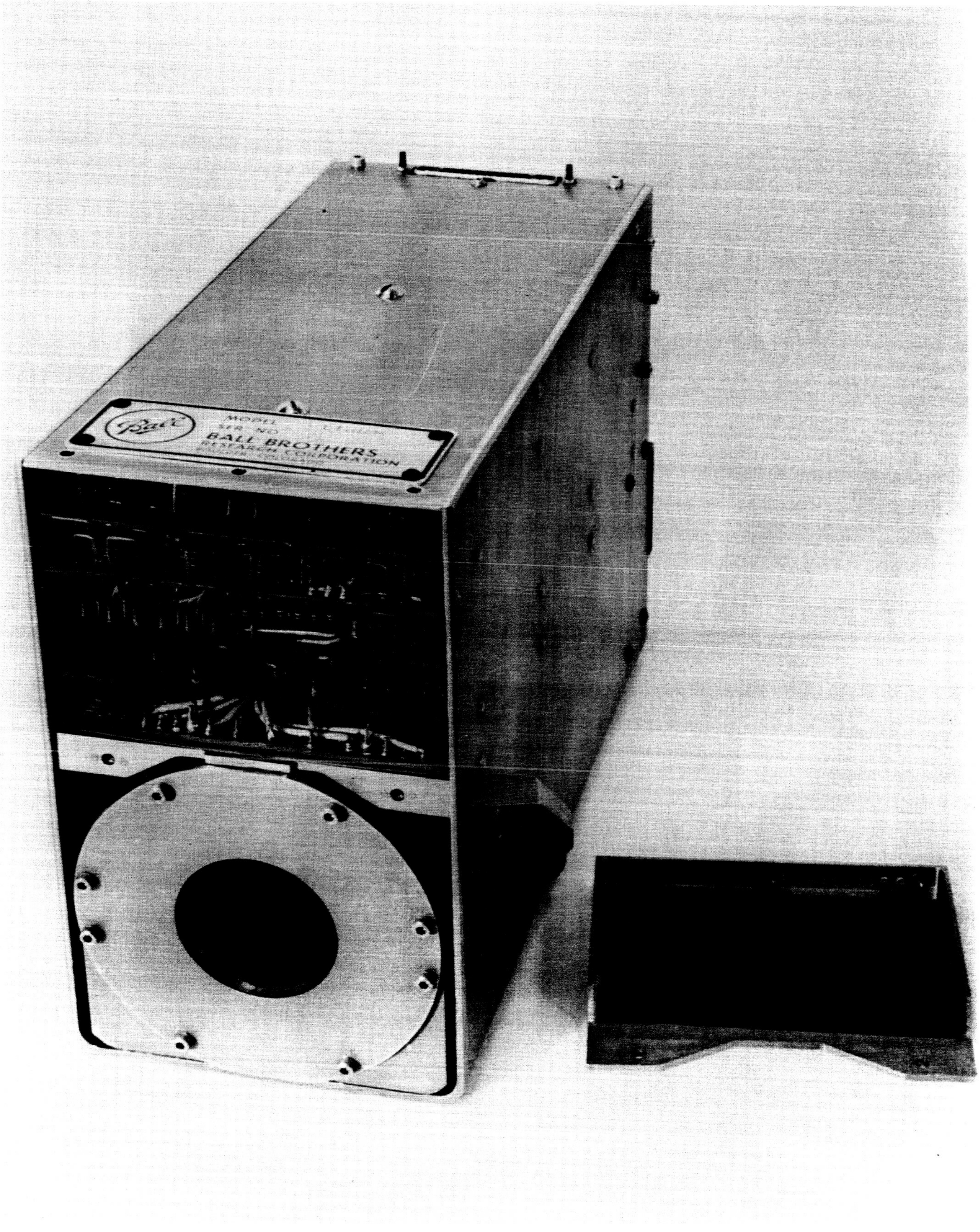
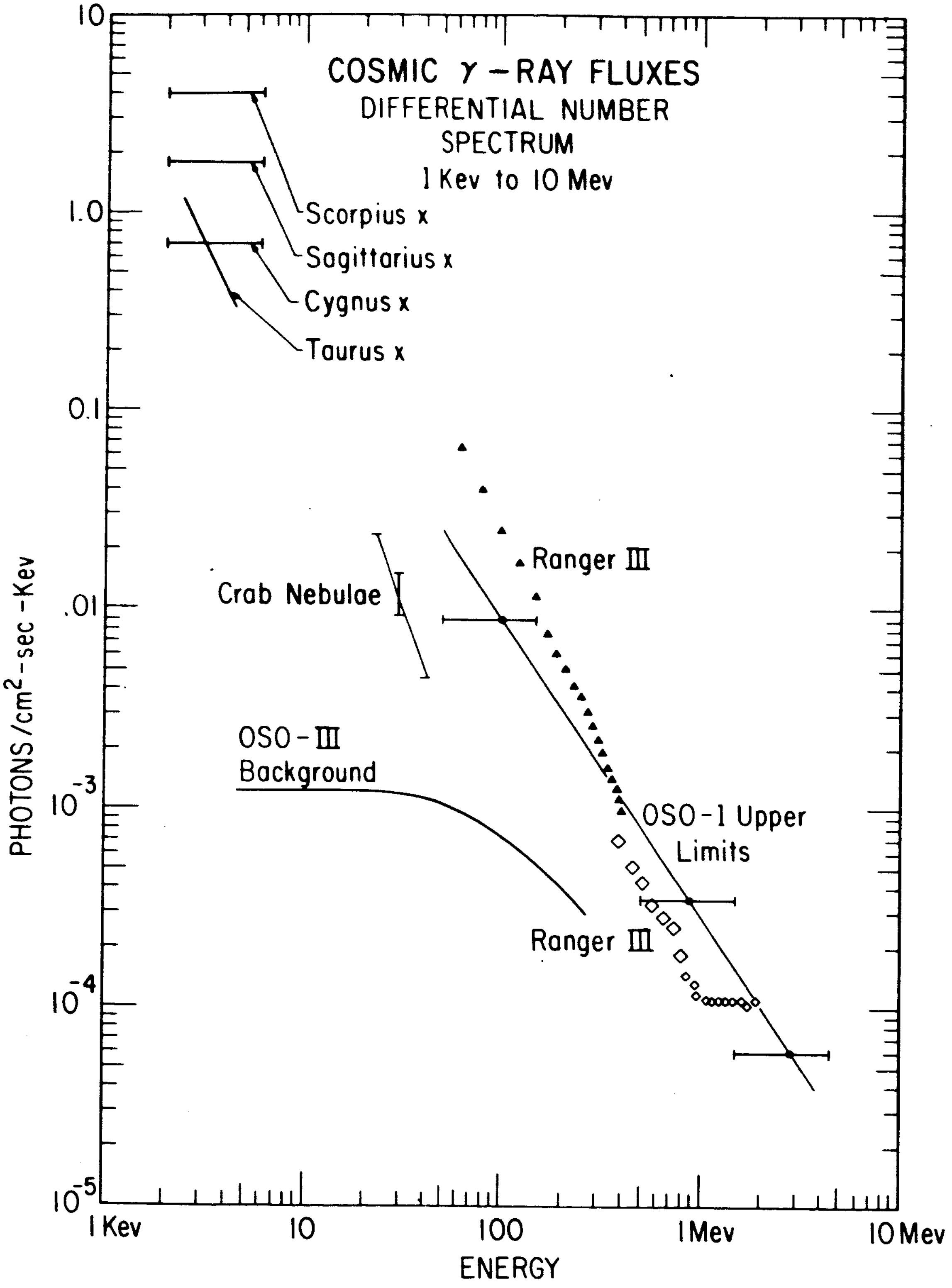


Figure 11



COSMIC γ - RAY FLUXES
DIFFERENTIAL NUMBER
SPECTRUM
1 Kev to 10 Mev
Scorpius x
Sagittarius x
Cygnus x
Taurus x
Ranger III
Crab Nebulae
OSO - III
Background
OSO-1 Upper
Limits
Ranger III
10
1.0
0.1
.01
10^{-3}
10^{-4}
10^{-5}
PHOTONS /cm^2-sec -Kev
1 Kev
10
100
1 Mev
10 Mev
ENERGY

Figure 12