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OBSERVATION OF PULSED GAMMA RAYS
WITH ENERGIES GREATER THAN 250 keV
FROM THE CRAB NEBULA PULSAR NP 0532

by

Larry E. Orwig
B.S., Lebanon Valley College, 1965



Space Science Center
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Durham

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A THESIS

Submitted to the University of New Hampshire
In Partial Fulfillment of
The Requirements for the Degree of
Doctor of Philosophy

Department of Physics
December 1971

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DEDICATION

I wish to express my most sincere gratitude to my wife, Lana, without whom this work would not have been possible.

ACKNOWLEDGEMENTS

The author would like to express his many thanks to Professor E. L. Chupp whose constant help and guidance throughout this effort is greatly appreciated. Special thanks also go to Dr. D. J. Forrest for countless discussions and many helpful suggestions and to Mr. Philip Dunphy and Mr. Andy Mammay for their assistance with the balloon flights. I also express my appreciation to Dr. C. Papaliolios for providing the pulsar phase and period information used in the analysis.

I wish to express gratitude to Mr. A. P. Wood and Mr. A. Knight for their help with the mechanical construction of the balloon payload, to Mr. R. Fells and Mr. P. Isaacson for their electronics design assistance, and to Messrs. P. Elkins, V. Deyo, and J. Googins for electronics assembly. Thanks also go to Mr. A. Gajate, Mr. Chung-Wai Yue, and Mr. R. Staples for the computer programming and much of the data handling.

I also wish to express appreciation to Mrs. Mary Chupp, Miss Sara Frost, and Mrs. Patricia Ferguson for their excellent job of typing the initial drafts; to Mrs. Pearl Libby and Miss Anne Kohl for typing the final manuscript, and to Mr. Dan Gats and Miss Janet Varney for their fine work on the diagrams and graphical work contained in the thesis.

The latter stages of this research effort were supported by the National Aeronautics and Space Administration under Grant NGL-30-002-021.

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ABSTRACT

OBSERVATION OF PULSED GAMMA RAYS WITH ENERGIES GREATER THAN 250 keV FROM THE CRAB NEBULA PULSAR NP 0532

by

LARRY E. ORWIG

Data from a balloon flight experiment using an 11 1/2" diameter x 4" thick NaI scintillation spectrometer have been analyzed to search for gamma ray pulsations from the pulsar NP 0532. The flight was conducted on June 7, 1970, and the payload was carried to a nominal atmospheric depth of 3.5 g/cm². The detector was pointing in the direction of the Crab Nebula for the entire time at float altitude. A superposed epoch analysis was performed on a 12,000 second portion of the data spanning a total time interval of 16,700 seconds at float altitude. A positive pulsed contribution was observed at the expected apparent frequency of NP 0532 having the double pulse structure typical of NP 0532. The results indicate a time-averaged pulsed photon flux of $(1.44 \pm 0.57) \times 10^{-3}$ photons cm⁻² sec⁻¹ in the energy interval from 250 keV to 2.3 MeV. This represents a time-averaged pulsed power of $I = (6.49 \pm 2.57) \times 10^{-4}$ keV cm⁻² sec⁻¹ keV⁻¹. The ratio of interpulse to main pulse was found to be 2.4 ± 1.9 . A further subdivision of the energy interval was performed to obtain spectral information above 250 keV. Although the data is statistically

very marginal, the analysis indicates a positive photon flux from 250 keV to 725 keV of $(1.20 \pm 0.52) \times 10^{-3}$ photons $\text{cm}^{-2}\text{sec}^{-1}$ or a time-average pulsed power of $(1.14 \pm 0.50) \times 10^{-3} \text{ keV cm}^{-2}\text{sec}^{-1}\text{keV}^{-1}$. Above 725 keV no pulsed contribution was found. Therefore, upper limits at the 95% confidence level were obtained for two energy bins, one extending from 725 keV to 2.3 MeV, and the second an integral channel above 2.3 MeV. No evidence was found for an enhancement in the pulsed flux at the 0.5 MeV annihilation line region.

SECTION I

INTRODUCTION

1.1 Gamma Ray Astronomy

Until the past half decade the field of gamma ray astronomy has been noted for its paucity of positive observations, being overshadowed by its companion field of X-ray astronomy. By gamma rays we mean here photons of energy greater than 100 keV (corresponding to a frequency of $2.42 \times 10^{19} \text{ sec}^{-1}$ and a wavelength of $0.124 \text{ \AA}$), no matter what their origin. There has never been any question as to the importance of studying cosmic gamma radiation. These photons are the direct product of fundamental processes basic to high energy astrophysics and cosmic-ray physics. Gamma ray measurements can help answer questions about cosmic rays, interstellar matter, galactic magnetic fields, stars and the types of interactions occurring in the universe. A measurement of the spatial and energy distribution of gamma rays can give much information about cosmic-ray sources and their interaction mechanisms. Unlike charged cosmic rays, gamma rays are unaffected by the cosmic magnetic fields and hence travel in straight lines. This greatly facilitates an identification of their origin in time and space.

The difficulty with earth-based measurement of such radiation results from the strong attenuation of gamma rays in the earth's atmosphere. This requires that measurements be carried out from instruments on high-altitude balloons and artificial satellites. It has only been recently that

detectors have reached the sensitivity needed to detect the meager extraterrestrial fluxes of gamma radiation. It looks now as if we are at the threshold of meaningful discoveries, and the next decade should see tremendous advances in the field of gamma ray astronomy.

Only a very few observations of extraterrestrial gamma radiation presently exist. For our own sun, positive measurements of gamma ray bursts during solar flares have been made up to energies of ~ 500 keV. No quiet time solar gamma radiation has been seen (LINGENFELTER, 1969). Also, no monoenergetic line emission has been observed during a solar flare. These results exist in spite of theoretical predictions of measurable gamma ray fluxes from solar flares LINGENFELTER and RAMATY, 1967; LINGENFELTER, 1969) which are within the sensitivity of present detectors. A second positive result is the measurement of an interstellar flux of gamma rays, observed initially by METZGER et al. (1964) with detectors aboard the Ranger 3 and Ranger 5 spacecraft. VETTE et al. (1969) have extended these measurements to 6 MeV. These authors attribute the observed flux to a diffuse component of cosmic gamma radiation. No information on the isotropy of this gamma ray flux is available as yet.

In terms of point sources, there are several positive observations. The first high energy observation was the measurement of a line source contribution from the galactic center above 100 MeV seen by CLARK et al. (1968) with a detector aboard the OSO 3 spacecraft. The line source has also been observed by KNIFFEN and FICHTEL (1970). However, there is still some disagreement with this result as one other group with an equally sensitive instrument has failed to detect such emission (FRY et al., 1969). FRYE et al. (1969) have seen evidence for a point source of high energy

gamma rays above 50 MeV in the Sagittarius region, which they have denoted as Sgr γ -1. Recently FRYE and co-workers have presented evidence for two new point gamma ray sources ($E_\gamma > 100$ MeV) which lie near the galactic plane (FRYE et al., 1971). These results have not been confirmed as yet.

The only other known extraterrestrial source of gamma radiation, and the most intense, is the Crab Nebula which has been observed to emit steady and pulsed radiation up to energies of ~ 500 keV (HAYMES et al., 1968). Because it is such a prolific emitter of radiation, the Crab Nebula has probably become the most widely studied astrophysical body. At the time when data analysis was begun on the present experiment, evidence was given by HILLIER et al. (1970) for pulsed gamma rays from the Crab pulsar from 0.6 to 9 MeV. In this thesis I shall present the results of a positive measurement of the pulsed emission from the Crab Nebula in the gamma ray energy region above 250 keV.

In the remainder of this section we shall consider the experimental and theoretical aspects of the pulsar phenomenon with emphasis on the Crab Nebula and its pulsar, NP 0532.

1.2 The Pulsar Phenomenon

During 1967 observations of a new type of radio emitting object were made by a group of radio astronomers led by Anthony Hewish at the University of Cambridge, England. They discovered a point-like source giving periodic bursts of radio noise which they reported in February, 1968 (HEWISH et al., 1968). This new object was given the name "pulsar", because of the pulsing nature of its emission.

This first pulsar was designated PSR 1919+21 (or CP 1919) (the digits give the position of the source in Right Ascension; thus CP 1919 means Cambridge Pulsar at $19^h 19^m$). Also at Cambridge, PILKINGTON et al. (1968) found three pulsars at sites where radio interference had earlier been observed. The Cambridge observations were quickly verified and many groups continued the search for other such objects with rapid success. At this time over 100 such periodic radio sources have been observed, and the search is still continuing, although at a much less frenzied pace.

Early studies indicated the following observational facts:

1. The burst periods appeared extremely constant, being stable to 1 part in 10^8 . However, later measurements showed that the pulsar periods were increasing at a very slow rate.
2. Pulse-repetition periods of the first four pulsars discovered (PSR 1919+21, PSR 0834+06, PSR 0950+08 and PSR 1133+16) ranged from 0.253 sec to 1.337 sec.
3. The amplitude and pulse fine structure were quite complex and varied greatly from pulse to pulse. However, the envelope obtained from an average over many periods remained very constant from one observation to the next.
4. Pulsars appeared to be "on" about 3% of the time.
5. Radio dispersion measurements, with an assumed average electron density of interstellar space of 0.1 to .01 electron/cm³, indicated that the pulsars were probably 10^2 to 10^3 light years from the earth. We were thus observing rather local radio sources in our own Galaxy. The angular distribution of these sources also indicated a galactic origin.

6. The sources could not be resolved within the one-second-of-arc resolution of the best radio telescopes, which implied that they are quite small objects. The short pulse durations of the observed pulsars (20 to 40 ms) gave an upper limit to the size of the radio emitting object of $\sim 5 \times 10^3$ km, due to the fact that electromagnetic information can travel from one point in the source region to another only at the speed of light (~ 6000 km in 20 ms).

7. The radio signals from pulsars were found to be highly polarized ($\sim 90\%$) and usually in a plane. This polarization could, however, be due to propagation or path effects in the interstellar medium, and it was not definite from the early work whether this was a parameter of the source itself. Subsequent work has shown that polarization is indeed a source characteristic.

8. The sources were not visible optically.

These observational details provided theorists with a rather restricted picture of possible pulsar sources. The small size of these sources eliminated ordinary stars as candidates. Flares occurring on ordinary stars could account for pulsed signals, but not such precisely periodic ones, and an ordinary sunlike star would be visible optically. Rotating planets were also eliminated as possibilities, which narrowed down the possible candidates to white-dwarf stars and neutron stars. White-dwarf stars are well known high density (10^4 - 10^8 g/cm³) objects with degenerate electron-gas interiors and are observed as end products in stellar evolution; while neutron stars were small superdense (10^{11} - 10^{15} g/cm³) theoretical objects with degenerate nucleon-gas interiors which were thought to come into existence as the result of supernova explosions.

There was also the question of what type of motion could produce the observed periodicities - vibration, orbital motion, or rotation. Orbiting planets were eliminated if it is assumed that they do not exist without an optically visible parent sun. Pairs of orbiting white-dwarf stars were excluded because the minimum period for such a model was 1.7 sec (OSTRIKER 1971), and lower observational periods already existed. Pairs of orbiting neutron stars would yield an increase in the rate of pulsation due to the emission of gravitational radiation which must occur for an accelerated body. This would give a decrease in the pulsar period, just opposite to the observed period increases. A vibrational type of mechanism was excluded for both white-dwarfs and neutron stars. For white-dwarfs a pulsation period of 0.25 sec or less is difficult to obtain, and the vibrational period of a stable neutron star is too small (OSTRIKER, 1971). By elimination, a rotating object seemed to be required. The list of possible candidates had therefore been narrowed down to two suspects, a rotating white-dwarf or a rotating neutron star.

Theory predicts a minimum rotation period > 0.25 sec for a white-dwarf (ZELDOVICH and NOVIKOV, 1971). A rotating neutron star, being 100 times smaller in size and having a much higher density than a white-dwarf, could maintain stable rotation at much higher frequencies. Hence, the period value of about one second seemed to be a boundary for choosing between a white-dwarf or neutron star model. An observation of period values much less than this would strongly favor the neutron star hypothesis while almost eliminating the white-dwarf model.

The observation which clinched the decision in favor of a neutron-star hypothesis was made by D. H. Staelin and E. C. Reifenstein III at the National Radio Astronomy Observatory. In November, 1968, they announced the discovery of two pulsating radio sources in the vicinity of the Crab Nebula (STAE LIN AND RIEFENSTEIN, 1968). Shortly thereafter, the group at the Arecibo Radio Observatory revealed periodicity in one of these sources and identified the source as a pulsar (NP 0532) in the center of the Crab Nebula (COMELLA et al., 1969). Its 33 ms period has turned out to be the shortest period found to date and is much less than that allowed by a white-dwarf model. This was not the only evidence against a white-dwarf model. A study of individual pulse shapes of several pulsars by the Arecibo group uncovered very fast pulsing events, called marching subpulses, whose marching speed of 10 ms or less could not be explained in a rotating white-dwarf model. Additional evidence favoring a neutron star hypothesis came from the fact that the Crab Nebula is the remnant of an observed supernova explosion, just the proper event needed for the formation of a neutron star. Since this observation, one other fast radio pulsar has been found which is directly associated with the remnant of a supernova. This is the 89 ms period pulsar CP 0833 in the Vela supernova remnant.

At the present time the observed pulsar periods range from a low of 33 ms for the Crab pulsar NP 0532 to 3.75 sec for NP 0527, with the majority of periods being around 1 sec. Most pulsars have been observed to be slowing down at various rates, with the two shortest period pulsars, NP 0532 and CP 0833, having the largest slowdown rates. Indications are that small pulsar periods go with large slowdown rates and that both conditions imply young

celestial objects. On several occasions the period rate-of-change of a pulsar has been observed to change sign. The first observation of this speedup was in the Vela pulsar PSR 0833 (REICHLEY and DOWNS, 1969).

A final comment concerns the luminosity of such objects. Assuming a galactic origin for these sources, the time-averaged radio luminosities of $10^{-4} L_{\odot}$ are typical for pulsars. This is not an outstandingly bright object. However, during the pulses the peak luminosity becomes much larger, making such pulses some of the most powerful signals in the radio sky.

In the next section we shall discuss the Crab Nebula (and pulsar NP 0532), which, because of its unique properties has been studied in great detail since its discovery. Following that discussion, two of the most promising theories developed to explain the pulsar observations are presented.

1.3 The Crab Nebula and Pulsar NP 0532

The Crab Nebula is the huge gaseous remnant of a supernova explosion observed to occur in the year 1054 A. D. by Chinese Astronomers. The early supernova remnant was visible as a reddish-white object for 23 days and 635 nights, and its brilliance exceeded the brightest starlike objects in the nighttime sky, the planets Venus and Jupiter. The initial luminosity rapidly decreased and was replaced by the much lower luminosity of the long-lived expanding remnant. This remnant, which is now over 900 years old, is roughly 10 light-years in diameter and is still expanding at the rate of ~ 1300 km/sec. The Crab Nebula itself has been known to emit radiation over a large frequency spectrum -

radio, infrared, optical, and X-ray. The energy output of the total nebula was measured to be roughly 10^{31} watts (10^{38} ergs/sec), but the source of this energy output was unknown.

The discovery of the radio pulsar NP 0532 in the vicinity of the Crab Nebula brought renewed interest in this celestial object. Shortly thereafter optical pulsations were discovered with the same period and from the same location by COCKE et al. (1969). This first optical observation was quickly verified by NATHER et al. (1969) and by numerous experimenters since then, perhaps the most striking being the photographic observations of MILLER and WAMPLER (1969). These observations pinpointed the radio and optical pulsar with the location of the south-preceding star of the central double star in the Crab Nebula. On March 13, 1969 the rocket astronomy group at the Naval Research Laboratory led by Herbert Friedman, detected soft X-ray pulsations (0.5-10 keV) from the Crab Nebula (FRITZ et al., 1969). The period of these pulsations matched the radio and optical period. Measurements by a large number of groups have confirmed this result and have extended the spectral observations all the way to the gamma ray energy region.

The Crab pulsar NP 0532 is unique in several aspects:

1. It has the shortest period of any known pulsar and also the largest slowdown rate ($P \approx 33.1$ ms, $dP/dt \approx 36.5$ nsec/day).
2. It is the only pulsar which has been observed to emit radiation outside the radio band (it is the only optical, X-ray, and gamma ray pulsar).
3. It is one of two pulsars which have been identified with supernova remnants.

Figure I-1 shows a comparison of selected measurements of the Crab pulsar "light curves" in the radio, optical, and X-ray energy regions. The curves indicate a similar double pulse structure in all energy regions. However, as the frequency of the pulsed radiation increases, the interpulse peak becomes more intense relative to the main peak. The interpulse peak total intensity roughly equals that of the main peak in the optical band, and the ratio of interpulse peak intensity to main peak intensity continues to increase throughout the X-ray region. The separation between the main and interpulse peaks appears to decrease slightly from a value of ~ 14.5 ms in the radio (COMELLA et al., 1969) to ~ 13.0 ms in the soft and hard X-ray regions (for example, RAPPAPORT et al., 1971). These parameters are listed in Table I-1, along with other observed characteristics of NP 0532.

A second feature to notice from Figure I-1 is that in the radio and optical bands there is no pulsed contribution in the region between the peaks. In the soft and hard X-ray band a non-steady-Crab component does appear in this region. The results of KURFESS (1971) indicate that this interpeak emission increases significantly above 100 keV where it becomes a very appreciable percentage of the total pulsed flux. A preliminary publication on the present work (ORWIG et al., 1971) showed no evidence for this interpeak contribution. Indications that a more complex pulse structure may exist in the X-ray region have not been clarified as yet.

From Table I-1 we see that the percentage of pulsed to total Crab emission appears to be continually increasing with energy for energies above ~ 10 keV. At 10 keV there

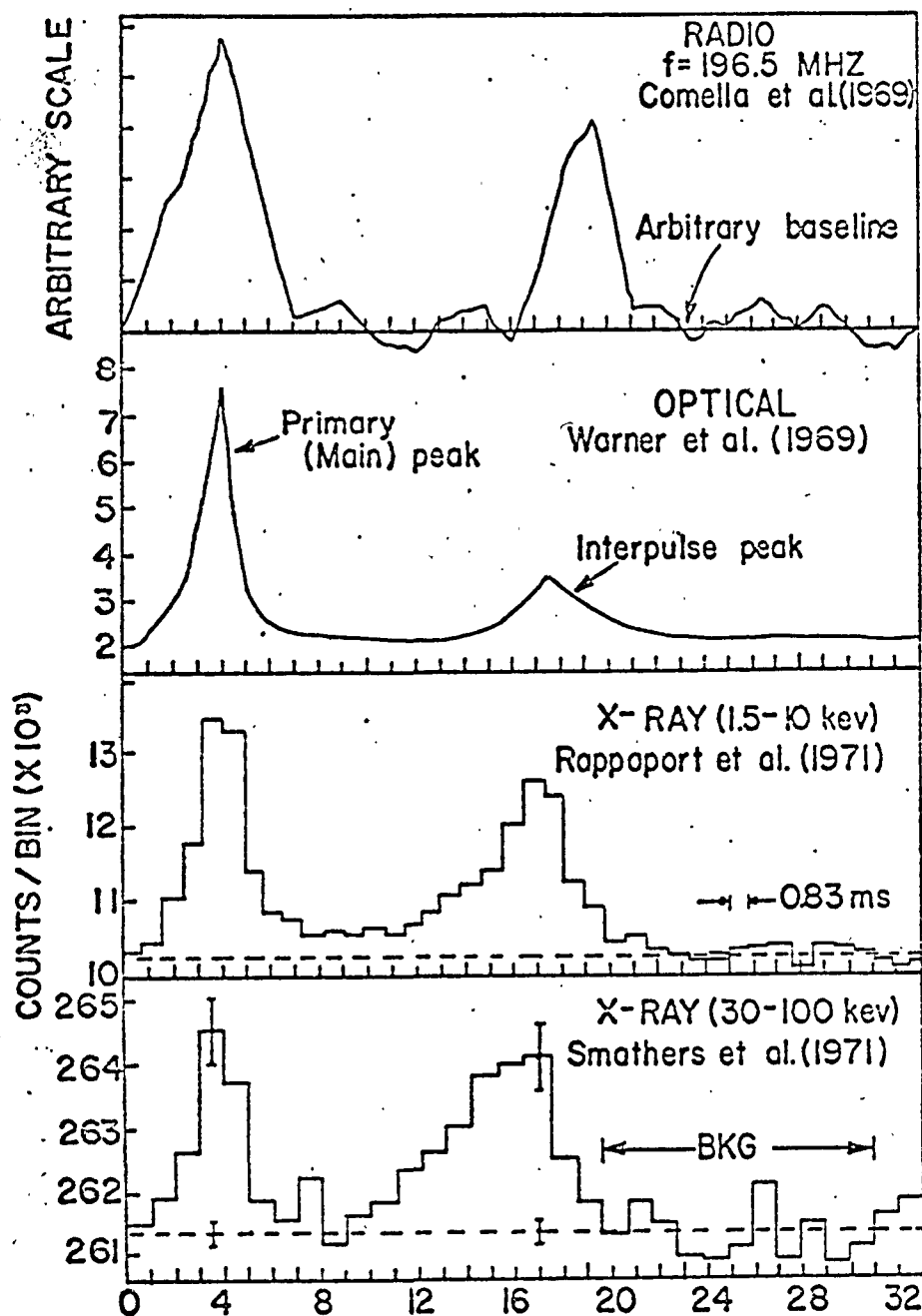


Figure I-1. Selected pulsar "light curve" measurements for NP 0532. The main peaks have been arbitrarily aligned with each other to provide a reference for time comparisons

TABLE I-1

CHARACTERISTICS OF NP 0532

REFERENCE	SPECTRAL REGION	MAIN-INTERPULSE SEPARATION (ms)	% PULSED	INTERPULSE INTENSITY/ MAIN PULSE INTENSITY
CONELLA ET AL. (1969)	RADIO - 196 MHz	14.50	-----	-----
WARNER ET AL. (1969)	OPTICAL-WHITE LIGHT	13.55	-----	0.59
PAPALIOLOS ET AL. (1970)	OPTICAL-WHITE LIGHT	13.38±0.03	-----	-----
FRITZ ET AL. (1969 A, B)	0.5 - 1 KEV		1.5±0.5	1.02±0.10
	6.0 - 9 KEV		10.0±2.0	
RAPPAPORT ET AL. (1971)	1.5 - 10 KEV	13.2 ±0.3	9.0±0.5	1.10±0.06
DUCROS ET AL. (1970)	20 KEV	13.1 ±0.5	16.70	
FLOYD ET AL. (1969)	25.0 - 100 KEV	14.0 ±1.0	15.0±5.0	1.7
BRIHI ET AL. (1971)	20.0 - 200 KEV	13.0 ±0.3	23.0±3.0	
SMATHERS ET AL. (1971)	30.0 - 100 KEV	12.7 ±0.4	20.0±4.0	2.05±0.30
HILLIER ET AL. (1970)	0.6 - 9 MeV	15.0 ±2.0	-----	3.2 ±1.6
ORWIG ET AL. (1971)*	0.25 - 2.3 MeV	13.0 ±2.0	-----	2.4 ±1.9
KURFESS (1971)	100.0 - 400 KEV	13.2 ±0.5	31.0±8.0	2.3 ±0.2
PRESENT EXPERIMENT	250.0 - 725 KEV	13.0 ±2.0	15.0±7.0	1.36±1.10

* EARLIER PUBLICATION OF PRELIMINARY RESULTS OF PRESENT EXPERIMENT.

seems to be a break in the pulsed fraction spectrum (as can be seen in Figure I-2), indicating a rapid decrease in pulsar flux relative to the steady Crab below 10 keV (FRITZ et al., 1971). There also appears to be a broad peak in the optical region of the pulsed radiation. These features are shown in Figure I-2 where the steady and pulsed Crab emissions are plotted versus energy. The graph is adapted from that of WOLTJER (1970) with certain recent measurements added. A more detailed plot of the present spectral measurements of NP 0532 in the X-ray and gamma ray energy regions is shown in Figure V-8. It is also interesting that no line emissions have been seen in any of the energy regions measured to date. This fact places a restriction on the emission mechanisms operating in the source regions.

The pulsed radio and optical radiation of NP 0532 is observed to be highly polarized (GRAHAM et al., 1970; WAMPLER et al., 1969), with the optical emission being linearly polarized with a polarization value of 15-20%. The plane of polarization is different for different phase points in the main and interpulse peaks. No positive X-ray polarization measurements exist for NP 0532. Also, the steady radiation from the Crab Nebula itself is observed to be polarized in the radio, optical, and X-ray energy bands.

1.4 Neutron Stars and Pulsar Models

Having covered the wealth of experimental observations on the Crab Nebula pulsar NP 0532, we now consider some attempts at theoretical explanations for these phenomena and for pulsars in general.

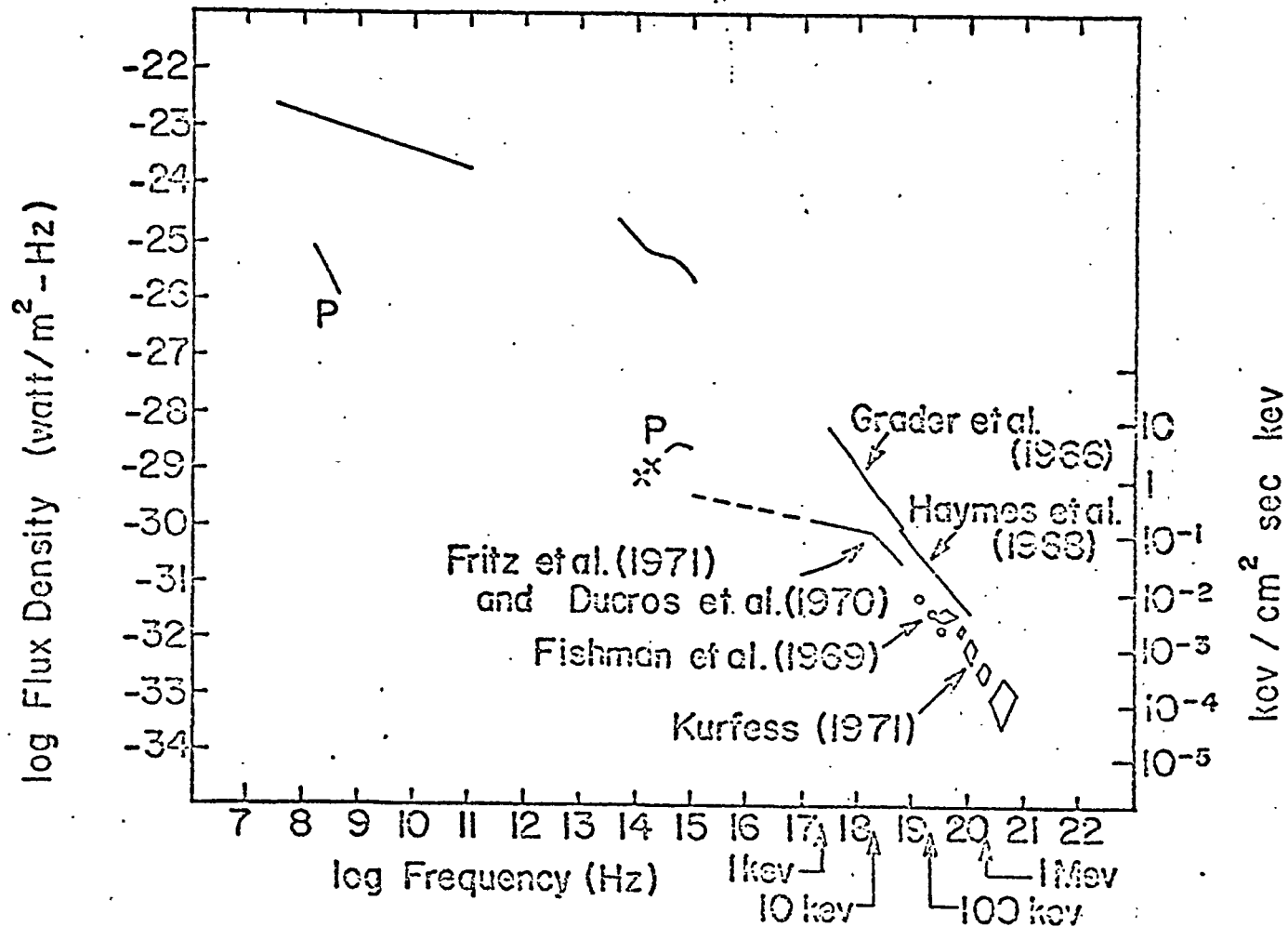


Figure I-2. Comparison of emission measurements of Crab Nebula and NP 0532. The graph is adapted from WOLTJER (1970) with the addition of the recent pulsar measurements of KURFESS (1971). Optical data is corrected for 1.5^m interstellar absorption in the visible. P denotes pulsed emission measurements of NP 0532.

The astrophysical body which many agree to be the cause of the pulsar phenomenon is the rotating neutron star. It was noted as early as the 1930's by BAADE and ZWICKY (1934) and OPPENHEIMER and VOLKOFF (1939) that such bodies could exist and be stable against gravitational attraction if they contained roughly one solar mass. Their existence was only postulated, however, until the discovery of pulsars. Extensive calculations of their properties and the association of their birth with supernova events, were made by WHEELER (1966), COLGATE and WHITE (1966) and A. G. W. CAMERON. An excellent study of their properties is found in ZELDOVICH and NOVIKOV (1971).

A description of the processes leading to neutron star formation is complex and relies heavily on general relativity. Only a simple qualitative picture is given here. Basically, a neutron star can be formed when a conventional massive star (the mass of which, however, cannot be much greater than 1.5 or 2 solar masses) begins to exhaust the nuclear fuels in its interior. The outer parts of the star begin to collapse rapidly under the strong gravitational forces. This collapse causes a tremendous pressure on the stellar interior which strips the electrons from the atoms in the star's core. Under the great pressure of contraction, this cloud of Fermi-electrons can combine with protons in the star's core by the inverse beta-decay process and form neutrons. At this point the star begins to implode catastrophically. The collapse continues until nearly all the electrons and protons have formed neutrons (there still remains a small number of protons and other nuclear particles), which become so closely packed that the nuclear repulsive forces begin to balance the gravitational collapse of the core and bring the collapse to a halt.

At this point the energy of collapse is believed to be converted into a huge shock wave which propagates outward, converting the kinetic energy of collapse into heat. This heating raises the temperature of the stellar surface regions to as high as 10^8 K, initiating a new phase of nuclear burning in the star's envelope which in turn generates more heat. Finally, a thermal shock wave forms and explodes the star's outer shell away from the core at relativistic speeds (the supernova explosion). The large thermal energy is converted into intense radiation, which we see in the optical band as the supernova explosion.

The remaining star core can, under rather restricted theoretical conditions, become a stable neutron star. Such stars are expected to be very small (~ 10 km in radius), contain approximately 1 solar mass, rotate rapidly, and contain surface magnetic fields of the order of 10^{12} gauss. Magnetic fields of this magnitude can be created when the parent star (having a typical surface field of ~ 100 gauss) collapses such that the field lines become frozen-in. Thus, a star of radius 10^6 km can evolve into a neutron star of radius 10 km and average surface magnetic field $B_s = 10^{12}$ gauss (OSTRIKER and GUNN, 1969).

The parent stars of neutron stars (and pulsars) are thought to be massive bright blue stars, since both these types of stars and pulsars appear to have the same distribution in the galactic plane (OSTRIKER, 1971). Such massive stars are known to rotate rapidly with typical periods $\lesssim 10^5$ sec. If angular momentum is conserved in the collapse, and allowing for angular momentum losses due to gravitational radiation, the resulting neutron star will rotate with a period of $\sim 10^{-2}$ sec.

On the assumption that rotating neutron stars are the cause of the pulsar phenomenon, several predictions can be made (GOLD, 1969) which are independent of the specific mechanism for the pulsed radiation.

1. Pulse length and period should show a positive correlation.
2. Short periods will be associated with young neutron stars.
3. Supernova sites are likely positions for pulsars.
4. Pulsars should be slowing down due to loss of rotational energy of the neutron star.

Positive evidence of all the above conditions has been obtained from pulsar observations.

Having established the likelihood that a rotating neutron star is the seat of the pulsar phenomenon, theorists were quick to originate a number of models which would explain the observations. One such model was put forth by Thomas Gold shortly after the discovery of the first pulsars (GOLD, 1968 and 1969). The heart of the Gold model is the rapidly spinning neutron star with a strong surface magnetic field ($\sim 10^{12}$ gauss) and a co-rotating magnetosphere. The field is assumed to be axially symmetric. At some distance from the star the co-rotation of the magnetosphere will cease to exist. It is expected that this co-rotation can be supported out to a distance at which the tangential speed of the magnetosphere would be close to the speed of light, $r_0 = c/\omega$. This surface is referred to as the "velocity of light cylinder". At this circle the magnetic field strength would be on the order of $10^3 - 10^4$ gauss. Plasma ejected from certain sectors of the surface of the star from flaring type processes will be constrained to spiral outward around the co-rotating magnetic field lines and will be accelerated

to relativistic speeds. At a point near the velocity of light cylinder this relativistic plasma will emit radiation. This radiation is strongly peaked in the tangential direction, and would act like a search-light beam which periodically sweeps past the observer at the rotation rate of the neutron star. Radiation from a sufficiently relativistic plasma can easily provide for the emission observed from radio to X-ray wavelengths.

In this model the rotation of the central neutron star provides the basic pulsar timing mechanism. The fine structure and variations in the intensity of the pulsed emission are a consequence of the variability and distribution of the plasma-emitting regions on the neutron star. Gold points out that in order to obtain the observed power densities of emitted radio radiation, a highly coherent type of emitting process is required. This could be provided by non-uniform static distributions of charges in the relativistic region. The model does not consider how such static distributions can be maintained in this region. Each neutron star would therefore be quite different from the next with respect to the detailed fine structure of the emission. Asymmetries in the radiation pattern could also result from a non-axially symmetric field or plasma content as well as a skewed or non-dipole field.

Beyond the velocity of light cylinder the magnetic field intensity will diminish, and the field lines perhaps become tangled. Some of the relativistic proton-electron plasma can therefore escape into the region beyond the velocity of light cylinder, which provides an energy source of relativistic particles for an expanding nebular cloud.

Calculations for the Crab Nebula indicate that the energy carried away by this relativistic gas could provide

enough energy in the form of relativistic electrons to explain the luminosity of the Crab Nebula. In this regard, SHKLOVSKY (1970) has pointed out that the synchrotron emission from a common source of relativistic particles can explain both the pulsar and steady Crab spectral emission features. This is consistent with the Gold model where the same plasma produces both radiations, but in different regions of the nebula.

A second plausible theory does not treat the origin of the pulses themselves, but deals with the mechanism of energy and angular momentum transfer from a highly magnetic rotating neutron star. The present theory is a fully developed version by J. Gunn and J. Ostriker (GUNN and OSTRIKER, 1969; OSTRIKER and GUNN, 1969 and 1970) of an idea put forth by PACINI (1968). This model treats the case where the magnetic dipole axis of the rotating neutron star is not aligned with the rotation axis. The authors point out that this non-alignment is essential for pulsars, because the appearance of axially symmetric stars is time independent and pulses would not exist. In their model the closed dipole field configuration will exist out to the velocity of light cylinder. Beyond this point the field lines depart from a dipole configuration and are swept back into a spiral pattern. Classical electromagnetic theory predicts that low frequency magnetic dipole radiation must be emitted by such a rotating body in a vacuum. Such multipole radiation will consist of very intense low frequency electromagnetic radiation which can extend beyond the co-rotating region. In addition, gravitational quadrupole radiation will be emitted if the body has a mass quadrupole moment. According to the theory, electric dipole radiation is nonexistent because of symmetry, and the electric quadrupole moment is only 10^{-37} as large as

the gravitational quadrupole moment (OSTRIKER and GUNN, 1969).

Under the assumptions that the moment of inertia of the body is constant, the body is not deformed during the rotation and that there is no alignment of the rotation and dipole axes during rotation, Ostriker and Gunn are able to derive expressions for the energy loss for this process and the age of a body emitting this multipole radiation. When applied to the Crab pulsar the energy loss in the form of intense 30 Hz magnetic dipole radiation is $\sim 10^{38}$ ergs/sec, in good agreement with the energy loss needed in the form of relativistic electrons to obtain the observed luminosity of the Crab Nebula (HAYMES et al., 1968). Their age of 1170 yr is in error by about 25% from the known 917 yr age of the pulsar. This age discrepancy can be removed, however, by the emission of large amounts of gravitational radiation during the early life of the neutron star, as is expected on theoretical grounds. The emission of this multipole radiation will cause the star to lose angular momentum at a calculable rate, which allows the period decay of the pulsar to be predicted. Using the measured slowdown rate for the Crab pulsar, they are able to calculate the surface magnetic field necessary to get the observed slowdown. They obtain a value of 2.6×10^{12} gauss for the surface field which agrees well with that expected for neutron stars. Finally, if they assume a decaying magnetic dipole moment of the form $m = m_0 \exp(-t/t_d)$ they find that the period does not become indefinitely long, but will stop changing when it reaches a certain value. On this basis they predict the termination of radiation from pulsars after $\sim 10^7$ yrs, which is thought to be the lifetime of typical pulsars. This would explain the absence of very long period pulsars in the observations.

By considering the motion of a test particle in this low frequency radiation field, they find that these intense multipole fields are an extremely efficient accelerator of charged particles. In the strong magnetic dipole wave field charged particles are accelerated in the propagation direction to nearly the velocity of light in a fraction of a wavelength. Hence, they can ride the electromagnetic waves outward at nearly constant phase and slowly gain energy from the wave (GUNN and OSTRIKER, 1969). For the Crab Nebula maximum electron energies of 5×10^{13} eV can be obtained by this process, and the energy input to the electrons is calculated to be $\sim 8 \times 10^{37}$ ergs/sec, in excellent agreement with the energy rate needed to replenish the synchrotron radiation losses of the nebula.

In the Gunn and Ostriker model the rotational energy of the neutron star is dissipated as low frequency multipole radiation. As in the Gold model, the rotation of the central neutron star is assumed to provide the basic pulsar timing mechanism. The mechanism which produces the pulsed radiation is not treated by these authors.

A number of theorists have considered mechanisms to explain the pulsed radiations. In addition to the very descriptive coherent plasma mechanism of GOLD (1968 and 1969), pulsar emission models have been proposed by LAYZER (1968), EASTLUND (1968), and MICHEL and TUCKER (1969). The problem is quite complex, owing to the very uncertain nature of the plasmas and fields surrounding a neutron star. The models are not fully developed enough to provide any concrete predictions against which observations can be compared.

1.5 Importance of Gamma Ray Measurements for NP 0532

Before considering the present pulsar search, it is important to consider briefly what may be learned from such gamma ray measurements. The observation of pulsed gamma rays from NP 0532 would, first of all, extend the spectral emission measurements to energies higher than have been seen previously from this unique celestial object. This extension of the pulsed spectrum would provide more information on the possible mechanisms which are effective in producing the pulsed radiation. As shown in Appendix A, a detailed knowledge of the spectrum shape can be quite crucial in choosing between different production mechanisms. The intensity of such gamma ray emission can provide information about conditions in the source regions of the pulsar. For example, if the measured pulsed spectrum is observed to cut off or decrease sharply at a certain energy, this may imply an upper limit to the energies to which particles can be accelerated in the source region. Conversely, a hard photon emission spectrum would imply that the acceleration mechanisms are very efficient particle accelerators, and that high particle energies are very likely. Thus, measurements in the low energy gamma ray energy region could have strong implications for proposed pulsar models.

An observation of pulsed line emissions from the pulsar would give direct evidence of specific nuclear reactions taking place in the pulsar source regions. Line flux intensities will give an indication of the actual densities of nuclei and reaction rates in the source. It is interesting to note that no pulsed line emissions have been observed from the Crab pulsar in any energy band.

In addition, it has been suggested by many authors that pulsars, and the supernova events to which they are intimately associated, could easily account for the origin of all cosmic rays. In this regard it has also been hypothesized that a sufficient distribution of these objects in time and space could provide the source of the observed diffuse X-ray and gamma ray background. If these suggestions are true, gamma ray measurements from one such pulsar would be extremely important.

For the Crab Nebula, the only gamma ray measurements of NP 0532 were those of HILLIER et al. (1970). Their results indicated that the pulsed emission had a very hard spectral shape, and that the pulsed emission could very likely be the total emission from the entire nebula at energies from 600 keV to 9 MeV. This, if true, would support the idea that the pulsing neutron star is the sole energy source for the whole nebula.

Fortunately, during the June 7, 1970 balloon flight of our large gamma ray spectrometer, the Crab Nebula was in full view of the detector. Motivated by the implications of Hillier's results and by the importance of gamma ray measurements of extraterrestrial objects, we initiated an investigation into the possibility of observing pulsed gamma ray emission from NP 0532 from our data. In the ensuing sections this investigation is presented.

SECTION II

EXPERIMENTAL APPARATUS

2.1 Detector Design Limitations

The gamma ray energy region of interest in the present experiment, extending from 200 keV to ~ 10 MeV is of particular experimental interest because of the difficulties involved in the detection of gamma rays in this range. This energy interval is unique in that it is above the region where standard X-ray detection methods can be employed (passive collimation) and below the region where no collimation is required for directional gamma ray astronomy measurements (using Cerenkov counters and spark chambers). Measurements in this region are performed almost exclusively by scintillation counter techniques. One difficulty arises because the efficiency for interaction of photons in the detector material is a minimum in this energy region. Hence, detection efficiencies are lower in this region than at lower and higher energies. This is shown in Figure II-1 where the mass absorption coefficient of NaI(Tl) is plotted against photon energy. For the same reason collimation is difficult, requiring very thick shielding to achieve worthwhile attenuation of background radiation.

A second effect which is detrimental to directional measurements in this region is the large production of secondaries in the detector and any shielding material surrounding the central detector. For this reason, early attempts at achieving directionality by passive collimation

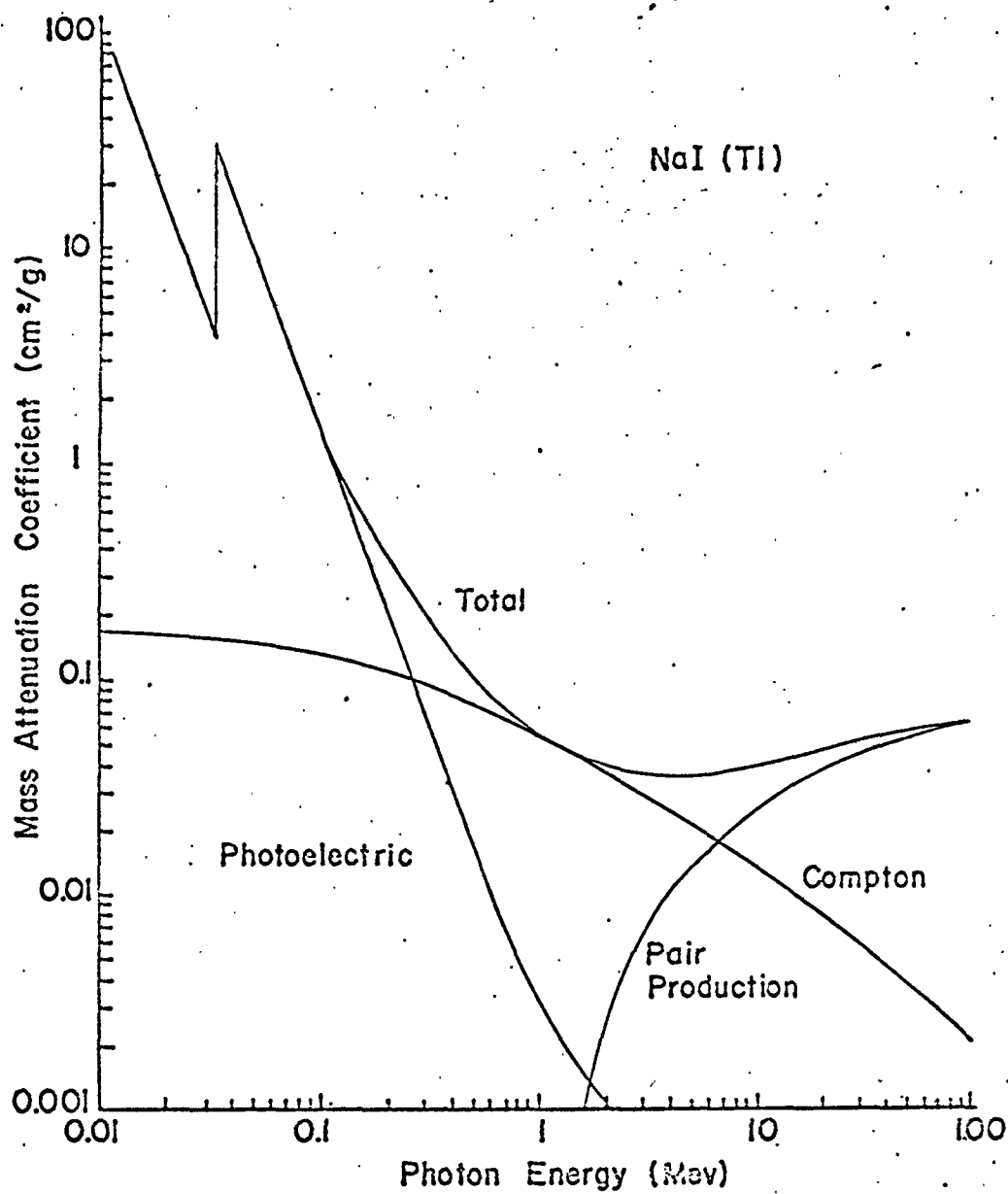


Figure II-1. Mass attenuation coefficients for photons in NaI(Tl) (EVANS, 1955).

failed because the large number of photons which are locally produced in the passive shield and subsequently impinge on the central detector cancel the attenuation effect of the shield material. In recent years some progress has been made with directional detectors in this energy region, using active collimating shields (see, for example, the unpublished HEAO proposals of PETERSON et al., 1970 and FROST et al., 1970). These difficulties combine to make the signal-to-background level quite low in this energy interval. These problems exist for any experiment which attempts measurements in the low energy gamma ray region, particularly those where directionality is a prime requirement.

In addition to these general design limitations, the experimental objectives of a given experiment dictate a specific set of design requirements for the detector system. At the time when the present detector system was being designed, the proposed experimental objectives were:

1. The primary experimental objective was the search for solar gamma rays in the energy interval ~ 200 keV to 10 MeV from balloon altitudes. This included measurements during both quiet and disturbed solar periods. Observed radiation can be identified as being of solar flare origin if it occurs in time coincidence with other observed flare phenomena such as radio and optical bursts and charged particle fluxes. For quiet time solar measurements, a typical technique for detectors having omnidirectional response is to perform day-night difference measurements. Particular emphasis was placed on the search for gamma ray line contributions at 0.511 MeV (annihilation line) and 2.23 MeV (deuteron formation line) as well as any other line fluxes.

2. As a secondary objective, this search would also extend to any other astrophysical body which is in the detector field of view during any of the balloon flights.

3. Secondary purposes for the experiment included a detailed study of the Earth's atmospheric gamma ray spectrum at balloon altitudes and at various atmospheric depths. This would possibly include the detailed measurements of the 0.511 MeV line flux as a function of zenith angle, atmospheric depth, and perhaps latitude to provide insight into the source of this line radiation in the atmosphere.

These experimental aims suggest a number of design criteria to be met by the detector system.

1. The detector should have good efficiency to enable measurement of low intensity signals in the presence of the large cosmic-ray induced background radiation in the atmosphere (see Appendix D). In this respect some method of reducing background radiation would be helpful in increasing the detector signal-to-background ratio. In essence what is required is a detector with directional response.

2. To enhance the ability to observe monoenergetic radiations, good detector energy resolution is necessary. The sensitivity of a detector for observing line radiation improves with improved energy resolution. A high photopeak efficiency is also desirable in this respect.

3. The instrument must have the ability to detect small enhancements in intensity over short time intervals (tens of seconds) such as might occur in solar flares. To meet this requirement, the detector should have a very high detection efficiency, and the electronics must be capable of handling high data rates without large deadtime losses. A high source counting rate is needed to obtain statistically significant results in a short time period.

4. To make any type of angular dependence measurement of the atmospheric gamma ray spectrum it is essential that the detector have some directional sensitivity for incoming gamma rays. This means that the detector is more sensitive to radiation from certain directions than others. (Here sensitivity is defined as the product of the projected area and efficiency of the detector for radiation from a given direction.) There are two approaches to obtaining directionality, either by using an active or passive collimator, or by utilizing the anisotropic sensitivity of an unshielded detector of special geometrical shape. These criteria dictate a detector with a high detection efficiency, good energy resolution, fast time response, and some directionality.

Perhaps the most often used figure of merit for a gamma ray detector is the upper limit flux which the detector is capable of observing in a given experiment. This figure is a measure of how sensitive the detector is to measuring signal contributions above background fluctuations and is important because it can be used to compare the detection sensitivity of different detectors. It expresses the minimum flux which a source can emit and just be seen by a detector above a certain confidence level. In equation form it is given by (CHUPP et al., 1968)

$$F(E, \Delta E) \gtrsim \frac{n}{\bar{S}(E)} \left[\frac{R_{S+B}(E, \Delta E)}{T_{S+B}} + \frac{R_B(E, \Delta E)}{T_B} \right]^{1/2} \exp[\lambda(E)\bar{d}],$$

where n is the number of standard deviations above background fluctuations which are required for a significant contribution (represents an arbitrarily chosen confidence level), $\bar{S}(E)$ is the average detector sensitivity (area-efficiency product) to parallel source radiation in the energy interval

ΔE , $R_{S+B}(E, \Delta E)$ and $R_B(E, \Delta E)$ are the average source plus background and background counting rates (counts/sec) respectively in the energy interval ΔE centered at E , and T_{S+B} , T_B are the source and background observing times (sec) respectively. The exponential term corrects the limit measured at an average atmospheric depth $\bar{d}$, to the top of the atmosphere. $\lambda(E)$ is the absorption coefficient for a gamma ray of energy E .

If the source contribution is much less than the background, $R_{S+B} \simeq R_B$, and assuming that equal time is spent on and off the source ($T_{S+B} \simeq T_B$), we have

$$F(E, \Delta E) \gtrsim \frac{n}{\bar{S}(E)} \left[\frac{2R_B(E, \Delta E)}{T_{S+B}} \right]^{1/2} \exp[\lambda(E)\bar{d}] \text{ photons cm}^{-2}\text{sec}^{-1}$$

II-1

Note that this flux limit calculation is based solely on fluctuations in counting statistics and does not include other non-statistical variations such as counting rate changes due to altitude drifts, latitude drifts, and gain shifts, which would yield higher upper limit values.

Equation II-1 shows that for a given balloon flight duration (T_{S+B}) and atmospheric depth, F can be reduced only by making the quantity $R_B^{1/2}/\bar{S}$ smaller. The two approaches to achieving this reduction are, (1) to decrease R_B , or (2) to increase the average sensitivity $\bar{S}$. The background counting rate can be reduced by collimated shielding around a central detector. Increasing $\bar{S}$ means using a large area, high efficiency detector. Note that if the detector sensitivity is isotropic, then $R_B \propto \bar{S}$, $F \propto 1/(\bar{S})^{1/2}$, and the only way to reduce F is to increase $\bar{S}$.

Using the upper limit flux value as a selection criterion, an extensive investigation into various detector designs was made. The results of this study indicated that two basic detector concepts were most useful.

1. a directional gamma ray spectrometer consisting of a central 3" x 3" NaI(Tl) crystal surrounded by an active cup-shaped collimating shield of thickness equivalent to 2" of NaI(Tl), or

2. a large area (diameter $\geq 8"$) large volume (thickness $\geq 2"$) unshielded NaI(Tl) gamma ray spectrometer which has directional properties due to its physical shape.

A low limiting flux value is obtained in the first case by minimizing R_B , and in the latter by trying to maximize $\bar{S}$.

A comparison of the two designs shows that the active collimating shield (which could be CsI(Tl), CsI(Na), NaI(Tl), thick plastic scintillator, or possibly a lead-glass scintillator) gives appreciable background reduction only for incident gamma rays of energies $\lesssim 1$ MeV or $\gtrsim 15$ MeV. From 1 to 15 MeV a reasonable size active collimator surrounding a small central detector represents only slight improvement over the large area disk-shaped spectrometer for directional response. In fact, the directional properties of the disk spectrometer are surprisingly good in this energy region (see Appendix B). Shields of sufficient thickness to give significant background reduction for the present experiment were extremely expensive and quite massive. For example, a plastic scintillator shield which is four interaction lengths thick at $E_\gamma = 0.51$ MeV would weigh ~ 1000 lbs. Equivalent thickness shields of inorganic scintillators would weigh nearly 200 lbs. Although directional response is obtainable with active shielding, it was felt that the

marginal improvement in directionality of reasonable size active shields over a disk-shaped unshielded detector did not justify the expense and problems expected in building a balloon payload with such shields.

This decision was also strengthened by the results of the upper limit flux calculations for each scheme, which showed that the unshielded large area spectrometer is capable of observing just as low an upper limit flux as the shielded detector. Limiting flux calculations were made to determine the sensitivity for observing line contributions at 0.511 and 2.23 MeV. The background counting rate under each line region was estimated from an extrapolation of the measured atmospheric gamma ray spectrum at a balloon altitude of 3.5 g/cm² (PETERSON et al., 1966). The results obtained for a disk-shaped spectrometer 11 1/2" in diameter x 4" thick ($\bar{S} \approx 545$ cm² at 0.51 MeV and $\bar{S} \approx 286$ cm² at 2.23 MeV), for parallel source radiation impinging on the flat surface of the detector and for an observing time $T \approx 10^4$ sec, are

$$F(0.51 \text{ MeV}) \gtrsim 7.3 \times 10^{-4} \text{ photons/cm}^2 \text{ sec}$$

$$F(2.23 \text{ MeV}) \gtrsim 2.3 \times 10^{-4} \text{ photons/cm}^2 \text{ sec}$$

These limits are based only on counting statistics. Essentially the same value at 0.51 MeV was obtained by FISHMAN et al. (1969b) for a 4" x 2" central spectrometer surrounded by a 2" thick NaI(Tl) cup. The limit at 2.23 MeV is significantly below the present solar flux limit at this energy (CHUPP et al., 1968).

Finally, the shielded detector has a poor response to short bursts of radiation due to the lower sensitivity in the "look" direction. A high sensitivity means a large number of source counts (and good statistics) from burst

events. The large spectrometer has the best time resolution of any detector scheme considered in the study. In fact, the time resolution for the chosen spectrometer was limited by electronics and not the detector itself.

2.2 Description of Detector

For the reasons described in section 2.1, a large volume disk-shaped NaI(Tl) spectrometer was chosen as the gamma ray detector. The final detector was an 11 1/2" diameter x 4" thick NaI(Tl) scintillation crystal, viewed by seven 3" diameter RCA 8054 phototubes. (A standard Matched Window Line assembly from Harshaw Chemical Co.). The tubes were operated in a gain-balanced mode with the anode pulses summed at a common point prior to preamplification. The crystal was housed in a low background stainless steel container, and in addition to individual netic-conetic magnetic shields around each phototube, low background stainless steel and teflon photomultiplier base assemblies were used. These low background precautions are very necessary with this large crystal since any intrinsic background line radiations from radioactive contaminants will produce a measurable effect in a short time due to the high photon interaction efficiency and large interaction volume.

This central crystal spectrometer was contained within a totally-enclosing active charged particle anti-coincidence shield. The shield was comprised of two overlapping cups of plastic scintillator (henceforth called CPSA and CPSB) as shown in Figure II-2. Each cup consisted of a 1 cm thick disk optically bonded to a hollow tube of 1 cm wall thickness. This overlapping cup design was chosen because it permitted an access path for the sturdy crystal mounting

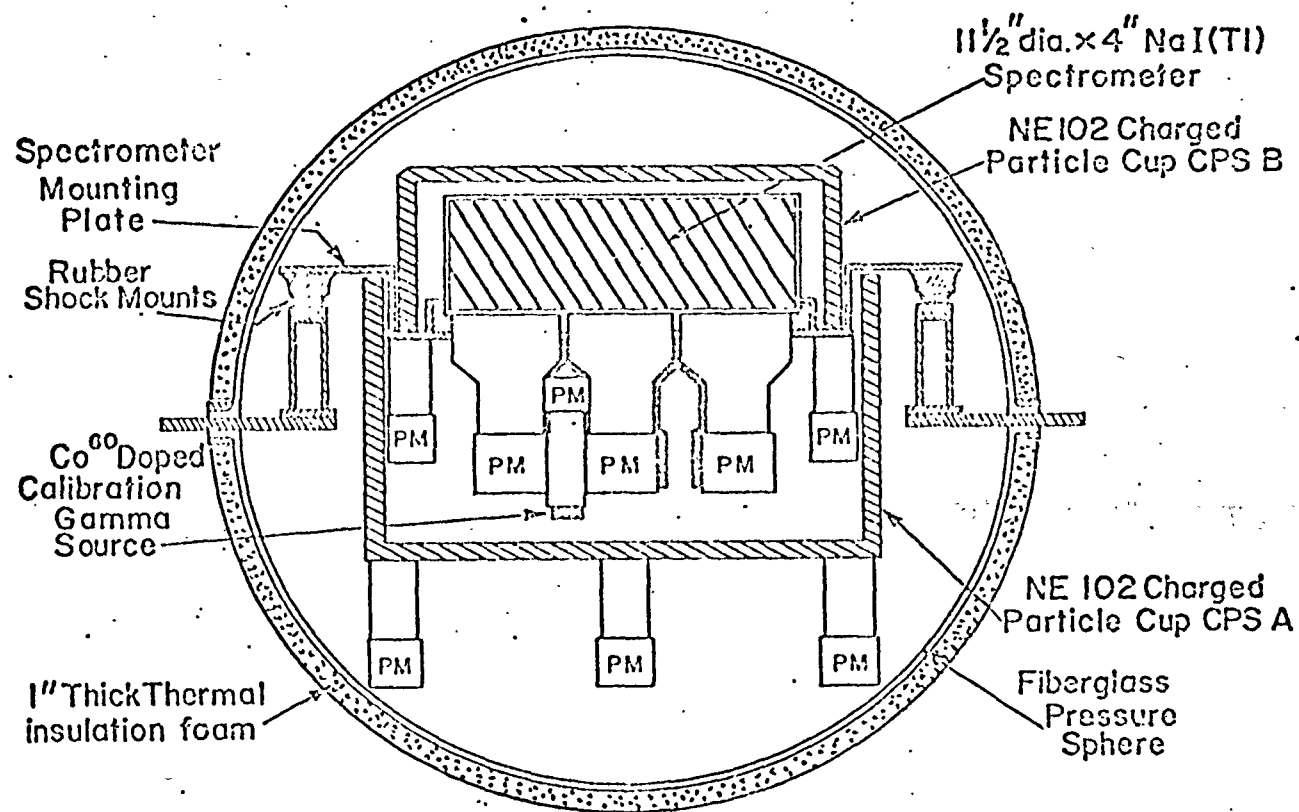


Figure II-2. Diagram of flight spectrometer showing position of various detector components.

frame while providing complete 4π charged particle coverage. All surfaces (except at phototube locations) were covered with tightly wrapped aluminum foil for good light collection, and the whole assembly was covered with black plastic and tape making a light-tight unit. Cups CPSA and CPSB were viewed by five and three 1 1/2" diameter RCA 6199 phototubes respectively at the locations indicated in Figure II-2. All phototubes for a given cup were wired in parallel, providing a single summed anode signal. Consequently, there were two such CPS signals since each cup was operated separately from the other, as shown in Figure II-3.

The 1 cm scintillator thickness was chosen as a compromise between two considerations, (1) assurance of sufficient light output to obtain a high efficiency for vetoing charged cosmic ray particles, and (2) minimization of the mass in the shield which could lead to production of mono-energetic deuteron formation gamma rays by thermalization and capture of atmospheric neutrons by the hydrogen in the scintillator. Due to the highly variable light travel paths between phototubes and different points of the cup, the light collection properties varied widely with position in each cup. Laboratory measurements showed that the rejection efficiency of each cup was $> 99\%$. This figure applies to the worst case operation of each cup since the measurements were made with a μ -meson telescope at the worst position for light collection. This is the position where a minimum ionizing through particle gives the smallest output signal. For the anti-coincidence shield as a whole, the rejection efficiency is much higher than the 99% figure. An extremely high rejection efficiency is not so crucial in this experiment because of the high counting rate from neutral events.

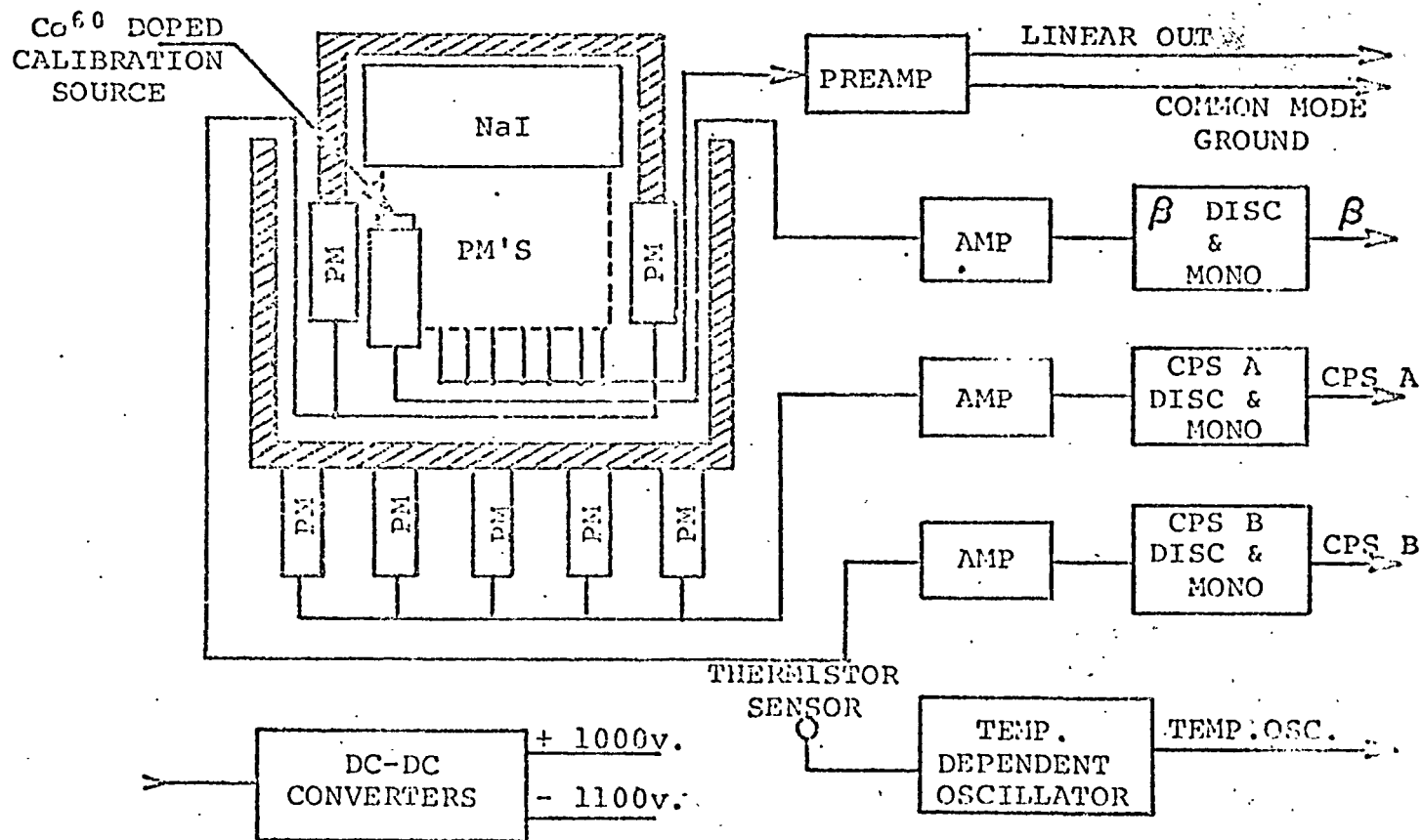


Figure II-3. Block diagram of flight electronics housed in detector pressure sphere.

A small leakage of undetected charged particles represents a much smaller percentage of total counts in a high counting rate experiment than it would in a low counting rate gamma ray experiment.

Two commercial DC-DC converters were used to supply phototube high voltages. One converter supplied positive high voltage (+1000v) to the seven phototubes viewing the crystal, while the second converter supplied negative high voltage (-1000v) for the eight CPS phototubes and the one calibration source phototube.

The NaI spectrometer, CPS cups, and certain electronics (see Figure II-3) were housed in a spherical fiber glass pressure container of wall thickness = 0.2 g/cm^2 . In addition, the preamplifier for the NaI signals, the CPS discriminators and shapers, and the calibration source beta event discriminator and shaper were contained in this sphere. As seen in Figure II-2, the mounting plate which supports the spectrometer and CPS cups was thermally isolated from the main support plate via rubber shock mounts, which also provided mechanical shock isolation for the NaI crystal. Strip heaters mounted on the detector mounting plate provided 28 watts of heating in the vicinity of the CPS cups. A thermistor-controlled astable oscillator housed inside the pressure sphere measured the free air temperature between the sphere and the detector. This temperature information was telemetered to ground and provided continuous information on the temperature of the detector environment.

2.3 The Detector Electronics

Effort was made to optimize certain design parameters in the instrument to remove problems experienced with earlier detectors flown by this group. In terms of electronics design, optimization in two areas was of prime consideration. An attempt was made to reduce the loss in spectrometer energy resolution in the electronics. For this reason high quality NIM standard modular amplifier and analog pulse handling electronics was used. Secondly, efforts were made to eliminate gain changes during the flight. A closed-loop digital gain stabilization system was incorporated into the flight electronics to help eliminate gain drift problems.

Figures II-3 and II-4 give complete block diagrams of the flight electronics. Those circuits shown in Figure II-3 were housed in the detector pressure sphere while those in Figure II-4, with the exception of VCO's and transmitters, were housed in a separate electronics pressure can. The summed CPS anode signal for each cup was amplified, and those signals exceeding a lower discriminator threshold were shaped into standard width logic signals. The same was true of the anode signal from the phototube viewing the calibration source. The linear NaI signal was preamplified before leaving the detector sphere. The preamplified NaI signals were fed to a Gaussian-shaping linear amplifier and delay, which provided prompt bipolar and delayed unipolar signals. All unipolar signals to be converted in the pulse height analyzer (PHA) were fed through the gain stabilization amplifier. The bipolar signals were used to generate timing pulses for use in the PHA and the gating logic section. The coincidence and anti-coincidence gating logic section contained the master decision-making circuitry for detector

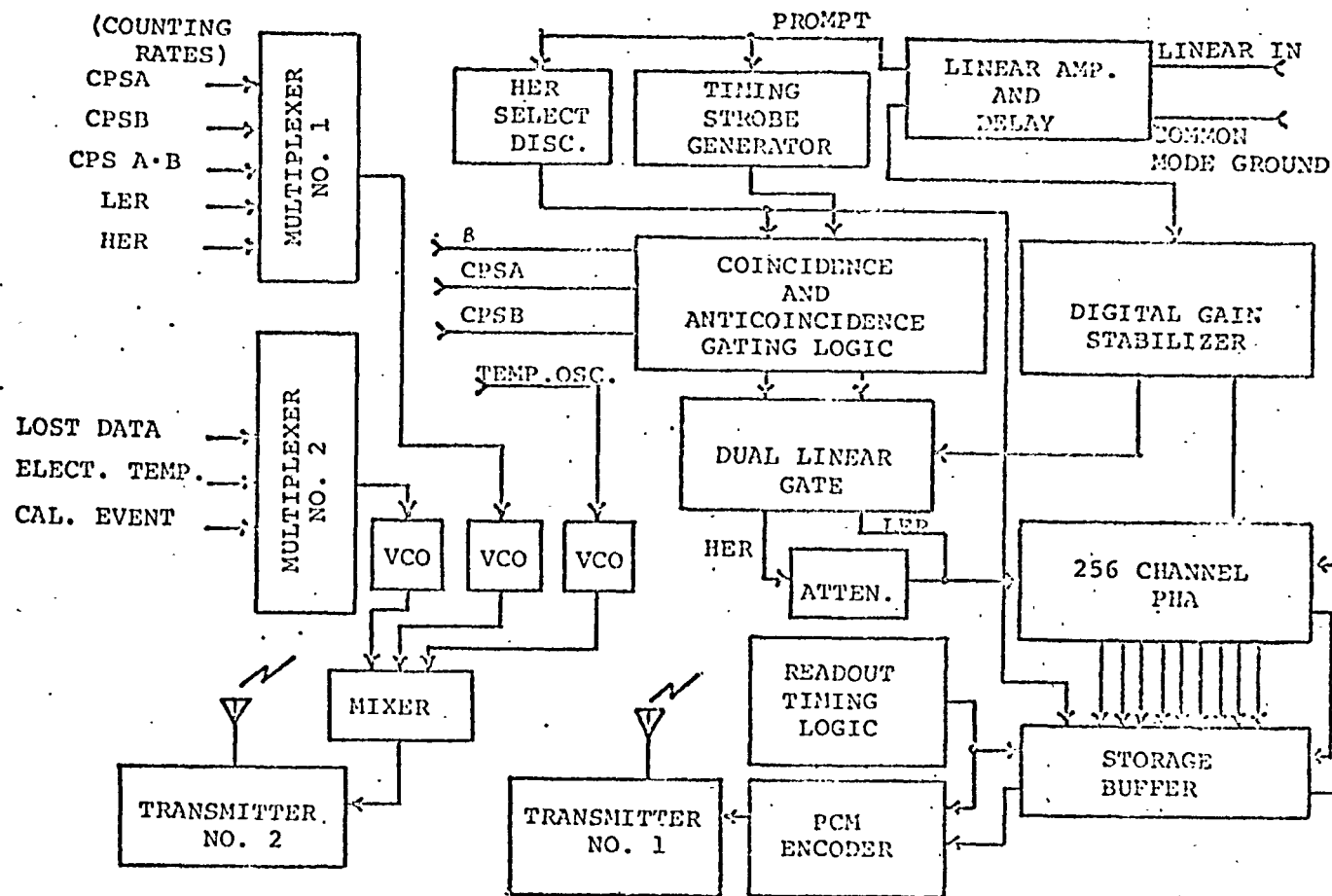


Figure II-4. Block diagram of flight electronics housed in electronics pressure can. Separately housed orientation system electronics is not shown here.

events. Those events occurring in the NaI detector and not accompanied by a simultaneous CPSA or CPSB signal ("neutral events") were steered to the 256 channel PHA for conversion. If a CPSA or CPSB pulse was simultaneously present, the event was vetoed.

Those pulses representing neutral events were divided into two contiguous energy ranges, the LER (low energy range) and HER (high energy range). Unipolar pulses whose amplitudes were insufficient to trigger a voltage threshold (HER SELECT DISC) were fed directly to the PHA. Pulses which triggered this threshold were attenuated before entering the PHA and became HER events. This signal steering was performed by the DUAL LINEAR GATE in Figure II-4. To distinguish between LER and HER events, a HER tag bit was generated whenever the HER SELECT DISC was triggered. This bit was then added to the parallel digital word which was entered into the buffer. This scheme enabled us to obtain up to 256 channels of pulse height information on each of the ranges and permitted us to use one PHA to cover a large energy range with good energy/channel resolution.

The parallel 9-bit digital pulse height information was then entered into a storage buffer. This derandomizing buffer was constructed from the design of PHILOKYPROU and ZACHARACOPOULOS (1968). The buffer accepted a random input rate, stored up to four events before becoming full, and was interrogated for readout at a periodic 3.57 kHz rate. This derandomization process greatly reduces deadtime losses which result from high input data rates and low telemetry transmission rates (see Appendix B). A full buffer caused the electronics to veto acceptance of further data by the PHA until a readout creates an empty buffer location. Those events that occur when either the PHA is busy or the buffer

is full are not accepted. This counting rate (called LOST DATA) is monitored during the flight. In the PCM encoder, the parallel digital information from the buffer is converted to a 12-bit serial PCM coded word and transmitted to ground at a 3.57 kHz word rate (50 kHz bit rate).

In addition to the pulse height analysis electronics, a complete monitoring system was used to handle housekeeping data. This system consisted of two 8-channel digital multiplexers which sequentially sampled various pertinent data. The sample rate was 1 channel/10 seconds, so that each data channel was sampled at least 10 seconds out of every 80 seconds. Figure II-4 shows the housekeeping data that was monitored on the second balloon flight. Inputs to the multiplexers were suitably scaled counting rates. The individual scaling factors, s_i , were chosen so that the error obtained in interpolating the demultiplexed data is less than the error due to statistical fluctuations in the unscaled input counting rates. Interpolation of scaled data is pointless when (EVANS, 1955) $u_i > (s_i - 1)^2 / \beta^2 s_i$, where s_i is the scaling factor for the i th channel, N_i is the total number of unscaled counts in a sample interval, β is the number of standard deviations in N_i , and u_i is the number of scaled counts obtained in the sample interval. This relation was used to select scaling factors for the housekeeping data. Each multiplexer output was fed directly to a subcarrier oscillator for transmission to ground using a second transmitter.

All flight electronics housed in the electronics pressure vessel were placed in a standard NIM bin. The well-regulated voltages for the electronics were obtained from battery-driven DC-DC converters. Primary electrical power was supplied by two stacks of Yardney Silvercel batteries,

the first a +9v, 40 ampere-hour stack for operating the 5v logic circuits, and the second a +30v, 40 ampere-hour stack to supply the NIM voltages. This type of battery was chosen because of its good power-to-weight ratio.

The batteries, DC-DC converters, and NIM bin were contained inside a 24" x 26" x 14" aluminum pressure vessel. All components were mounted on an aluminum base plate with rubber standoffs to provide thermal and mechanical shock isolation from the outside. A 1" thick polystyrene foam liner inside the can, in addition to white paint on the outside surface of the can, provided thermal control of the electronics. No heaters were needed in the pressure can since sufficient heat was dissipated by the electronics and batteries to maintain the temperature between +18°C and +35°C during the balloon flights. The electronics temperature was monitored by a thermistor-controlled oscillator (ELEC TEMP OSC) positioned directly above the NIM bin. Also, a clock-driven temperature recorder mounted inside the can recorded the free air temperature in the electronics pressure vessel.

2.4 Gain Stabilization System

To optimize the energy resolution of the detector system, very good gain stability must be maintained. Gain stabilization was achieved by electronically "locking on" a reference peak in the gamma ray spectrum and forcing this peak to remain in the same PHA channel at all times. If gain changes caused the peak to drift, the drift was sensed and a gain correction applied. The heart of the system was a commercial digital stabilizer which uses the digital PHA outputs to control a variable gain amplifier. The amplifier

correction was applied via a stepping-motor driven potentiometer. The in-flight calibrator source made use of the β -coincidence source method (CHUPP et al. 1968; FORREST et al. 1971) with Co^{60} as the radioactive source. The Co^{60} provides two distinct gamma ray calibration lines. For a detailed discussion of the method the reader is referred to CHUPP et al. (1968), and FORREST et al. (1971). Briefly, a phototube viewing a Co^{60} -doped plastic scintillator disk detected the beta particle emitted before the prompt coincident cascade gamma rays of energy 1.17 MeV and 1.33 MeV. The amplified phototube signal was fed to a discriminator (see Figure II-3) whose output was shaped to a standard width logic pulse. These pulses, which represent beta events in the source disk, were placed in coincidence with the neutral event signals from the NaI spectrometer. Those neutral events selected by this β - γ coincidence requirement were tagged as calibration events (CAL EV). The coincidence signal prevented entry of each CAL EV into the buffer. This means that no artificial calibration lines should appear in the transmitted data. (This is only true of course if the coincidence efficiency is 100%). The stabilization circuits were activated only by β - γ calibration events, making certain that gain corrections were controlled solely by calibration source signals. The stabilizer was adjusted to lock the 1.33 MeV Co^{60} reference peak in channel 113 of the LER spectrum for flight 558P.

Since the system operated from the digital outputs of the PHA, it corrected for all types of system drift up to and including the pulse height analyzer. For example, it corrected for phototube gain changes due to high voltage drift, amplifier gain changes due to thermal and high counting rate effects, and analog to digital conversion variations.

The only effect which the system was unable to compensate for was a zero level threshold shift in the amplifiers or the PHA. Preflight laboratory tests of the stabilization system showed satisfactory performance under simulated flight conditions.

The Co^{60} calibration source-phototube combination used in the present system had a source strength of 0.02 microcurie and a rejection efficiency of $\sim 75\% - 78\%$, so that only 22-25% of the calibration gamma rays could produce events which appear in the output spectrum. The choice of calibration source-to-crystal distance assured that the leakage rate of calibration source events was a small part of the total spectrum.

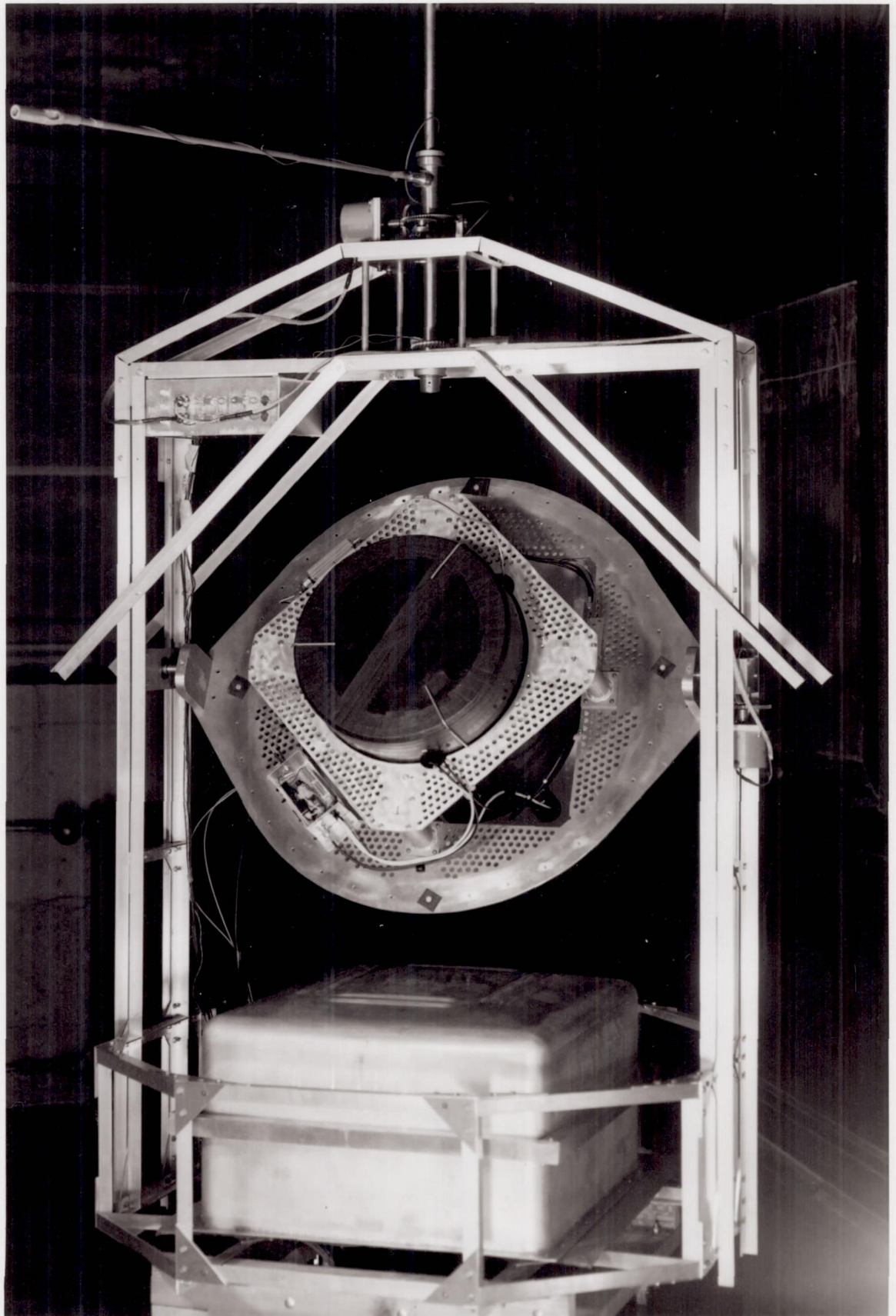
2.5 The Gondola and Orientation System

The entire flight detector system was mounted inside an aluminum gondola frame as shown in Figure II-5, where the positions of all major detector components can be seen. The large mass of electronics and its pressure vessel was placed as far away from the detector as possible to minimize neutron and gamma ray production effects. The gondola frame was designed to provide a sturdy but lightweight framework for mounting all system components.

Provisions were made to point the detector sphere using an orientation system designed and constructed specifically for these balloon flights. A detailed description of this system is given by ORWIG et al. (1970). Basically, the gondola frame is stabilized to a north-south magnetic field reference by means of a magnetometer-controlled servo system. This provides a stabilized platform. From this reference platform the detector sphere could be positioned

Figure II-5

Photograph of the UNH spectrometer payload and aluminum gondola. The detector is shown without the top pressure sphere cover. The can on the bottom of the frame houses the majority of the flight electronics. Also visible are the magnetometer at the end of the boom and the drive motors for the pointing system.



at any desired azimuth and elevation to an accuracy of $\pm 3^\circ$ on each axis by means of a fully digital, ground-commanded orientation system.

Movements about each of the two axes was achieved by controlling the number of steps taken by stepping motors. Movements in azimuth and elevation could be made in 1° , 10° , or 90° steps at an angular rate of $1^\circ/\text{sec}$. The entire gondola was rotationally decoupled from the balloon flight train via a swivel coupling. Movements about the azimuthal axis were made by rotating against a large dumbbell-shaped inertia reaction boom. By decoupling from the balloon, unnecessary rotational perturbations induced by the slow balloon rotation (~ 1 revolution per 5 to 15 min at float altitude) are eliminated.

The complete orientation system package also included provisions for the transmission of position information to ground and reception and verification of ground commands. The transmission of this information required two VCO telemetry channels. A complete ground station decoder provided visual display of the pointing angles and system commands during the flight. The magnetometer boom, orientation electronics box, and motor drives are visible in Figure II-5.

In the following section the ground support systems used for receiving, decoding, and recording the data are discussed.

2.6 Ground Support Systems

Figure II-6 shows a complete block diagram of the ground support systems used in the telemetry receiving station during the balloon flight. The PCM decoder-pulse height analysis section consisted of one VHF receiver, the

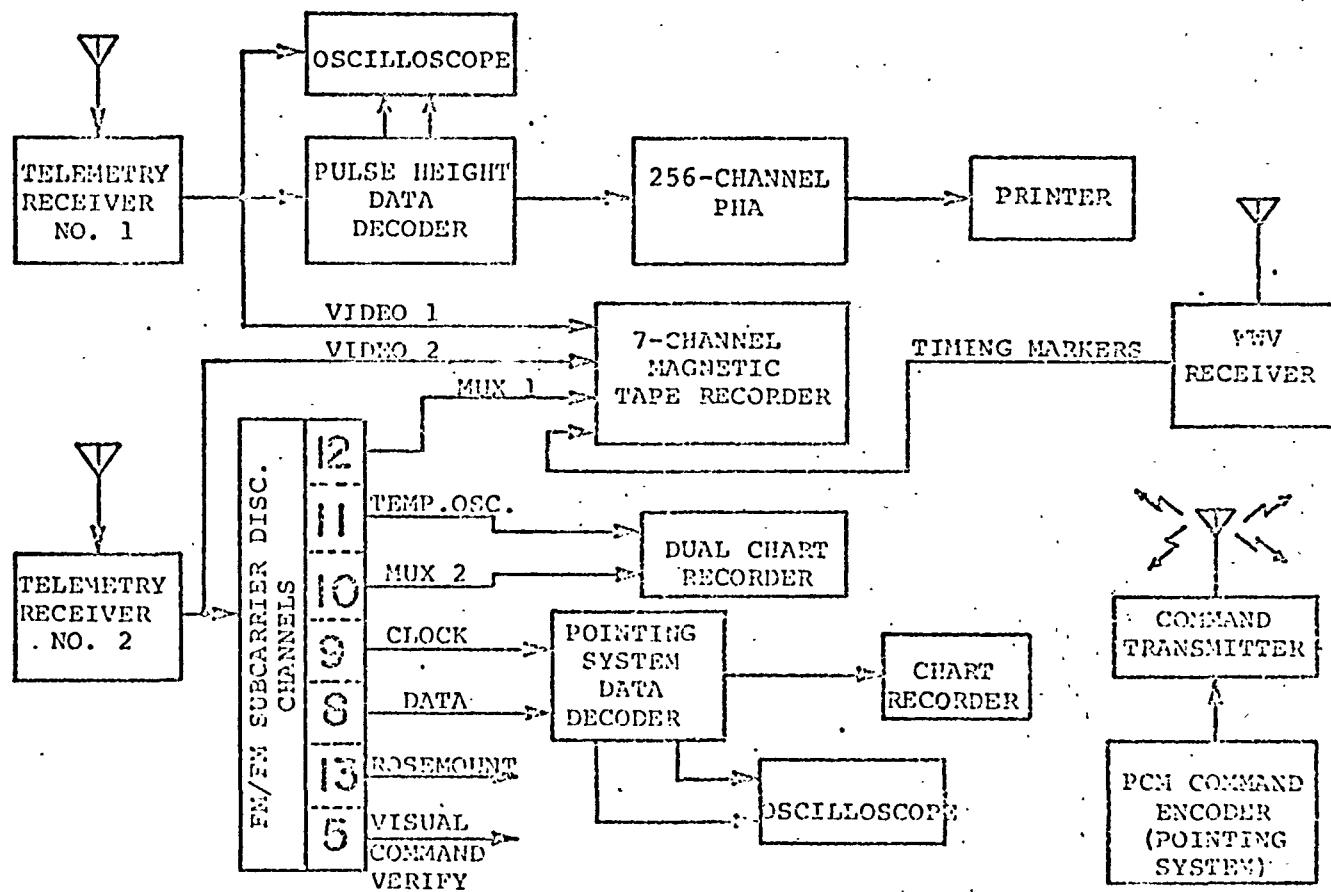


Figure II-6. Block diagram of ground support equipment used during flight in the telemetry receiving station at Palestine, Texas.

PCM decoder, a commercial 256 channel pulse height analyzer with printer readout, and one channel of an analog tape recorder. With this equipment real-time spectra were obtained during the balloon flight. In addition, the PCM pulse height information was recorded directly on one channel of the tape recorder for further use.

All housekeeping multiplexer data and orientation system data were received on a second VHF receiver, whose video output was recorded on a second channel of the tape recorder. In addition an array of FM/FM subcarrier discriminators were used to decode certain telemetered data for presentation to monitoring and recording devices, such as chart recorders and visual lamp displays. Chart recorders were used to give a quick look at the flight system operation and provide a hard copy of the data as well. The separate orientation system ground station had provisions for decoding and display of all pertinent pointing information.

All flight data was stored on magnetic tape. In addition, the timing signals from station WWV, Fort Collins, Colorado were received at the Palestine, Texas receiving station and simultaneously recorded on a separate track of the magnetic tape. This provided accurate timing for the recorded data. All results considered here were obtained from an analysis of the pulse height data which was stored on these magnetic tapes.

An extensive series of pre-flight and post-flight calibrations were carried out on the flight instrument. The interested reader is referred to Appendix B where the results of these instrument calibrations are presented in detail.

Two balloon flights were made with the flight instrument described above. These flights are discussed in the next section.

SECTION III

BALLOON FLIGHTS

3.1 Flight 517P

The detector system previously described was successfully flown on two balloon flights from the NCAR launch facility at Palestine, Texas. The first flight, designated as 517P, took place on November 26, 1969 and the second, designated as 558P, on June 7, 1970. The first flight, in addition to the primary objective of observing the Sun, was also intended as an engineering flight to check operation of all flight systems, including the initial test of the prototype model of the payload orientation system. Of particular interest were the questions of (1) how well the NIM modular electronics would operate under adverse temperature conditions, (2) how good was the temperature control of the instrument, (3) how well the large NaI crystal would stand up to actual flight conditions, and (4) how well the gain stabilization and payload orientation systems would operate.

The first flight was launched at 1350 UT (0750 CST) on November 26, 1969, reached float at a nominal atmospheric depth of 4.5 g/cm^2 at 1600 UT and remained approximately at that depth until cutdown at 1805 UT. The payload landed near Vernon, Alabama at 1841 UT. Due to high winds at float altitude, the maximum telemetry range was reached early causing float duration to be only two hours. Throughout the flight a predetermined series of pointing operations was performed which enabled a complete check of the orientation

system. At float altitude a number of alternate "on-sun, 90° away-from-sun" movements were successfully completed to obtain source plus background and background data for the Sun.

The data from this flight indicated the following results.

1. There was a permanent loss of housekeeping data at an altitude of 15.3 km and a loss of HER pulse height information at an altitude of 17.9 km.

2. There was a temporary loss of LER pulse height information between 12.1 and 17.2 km. This temporary malfunction appeared to be caused by the loss and subsequent reaquisition of the calibration peak by the gain stabilization system. In recovering the peak, large gain corrections were made by the system, which rendered the data unreliable during this period.

3. The detector and its pressure vessel as well as the electronics operated colder than expected.

4. The orientation system did not achieve the pointing accuracy for which it was designed. The payload was only stabilized to an accuracy of $\pm 10^\circ$ in the azimuthal direction. Since the large spectrometer has a "field of view" of $\sim 120^\circ$ FWHM, this 10° uncertainty presented no real limitation to the success of the experiment.

Based on the results of flight 517P, changes and improvements were made to the entire system to remove the difficulties experienced in the first flight. Minor electronics changes were made to assure more reliable operation. A new servo drive system incorporated into the orientation system improved the azimuthal pointing accuracy to $\pm 3^\circ$, removing the earlier problem. More work was done on the thermal control of the detector and electronics. Help in this area was given by Karl Stefan at NCAR, Boulder, Colorado.

Given our flight configuration, his group performed a thermal analysis of our system, which led to recommendations for better thermal control of the payload. The necessary changes were made prior to the second flight.

Finally, an on-board chart recorder used to record housekeeping data in the first flight was replaced by the two 8-channel electronic multiplexers described in section 2.3. This change was made because of a failure of the on-board chart recorder in the first flight.

3.2 Flight 558P

The data which form the basis of this thesis were obtained from the second balloon flight of the instrument, NCAR flight 558P, launched on June 7, 1970. The complete UNH scientific payload, including gondola, weighed ~ 575 lbs and was flown on a 0.7 mil Winzen $10.6 \times 10^6 \text{ ft}^3$ balloon. The total weight of the payload, including 250 lbs of ballast, NCAR support electronics, and telemetry equipment was ~ 955 lbs at launch. Figure III-1 shows a diagram of the balloon flight train.

Approximately 380 lbs of this weight was taken up by the standard balloon flight control package provided by NCAR. Most of this package was located at the bottom of the gondola as far away from the detector as possible (see Figure III-1). In addition to 250 lbs of ballast, this package contained:

1. A barotransmitter which provided coded pressure (altitude) data from launch until cutdown.
2. A Rosemount Model 830-A pressure transducer gauge used for accurate pressure readings at atmospheric depths $\lesssim 10$ mb. This gauge is calibrated by NCAR and has a

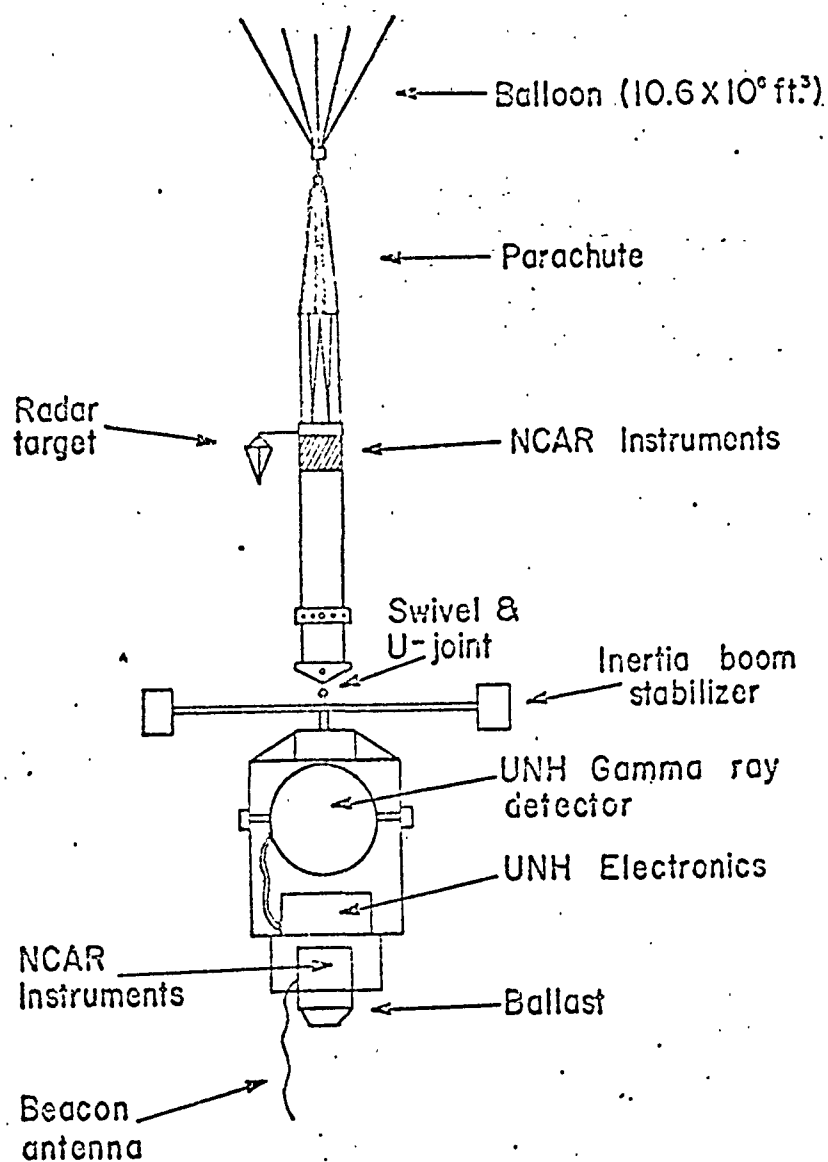


Figure III-1. Complete balloon flight train for flight 558P showing both the UNH and NCAR payloads.

measured pressure accuracy of ± 0.1 mb at float altitudes of 1-7 mb.

3. A receiver and decoder for the NCAR PCM command system (utilized for ground control of the pointing system).

4. A receiver and decoder for NCAR ballast and cut-down commands.

5. A Rawinsonde package which provided external temperature readings from a thermistor sensor and indirect balloon position readings until float altitude was reached.

After a smooth launch at 1153 UT (0653 CDT) and normal ascent, the balloon reached float at an atmospheric depth of 3.5 gm/cm^2 at 1415 UT and remained at an atmospheric depth of 3.2 to 3.9 g/cm^2 for approximately 7 1/2 hrs until flight termination by NCAR ground command at 2145 UT.

Following a 40 minute parachute descent, the package landed seven miles WNW of Monahans, Texas at 2234 UT. Due to high surface winds in the descent area after landing, the payload was dragged by the open parachute nearly 1/2 mile on the ground before coming to rest. Considerable external damage occurred to the aluminum gondola frame, including some of the gears and shafts of the orientation system. The four detector mounting posts (those posts which held the NaI detector, CPS A, and CPS B to the main mounting plate; see Figure II-2) were sheared off. This allowed the detector to float freely inside the upper half of the pressure sphere. Also, the detector pressure sphere was ruptured by broken aluminum frame supports. Post-flight tests showed no damage to the NaI spectrometer or plastic CPS cups. However, two RCA 6199 phototubes viewing the bottom of CPS A were broken, presumably when the detector mounts were broken. Except for a number of severed electrical cables, no damage occurred to the electronics and its pressure vessel.

3.3 Performance of Flight Instruments

All balloon flight systems operated quite well with one minor exception discussed at the end of this section. The electronics pressure can temperature sensors indicated that the temperature inside the can remained between $+18^{\circ}\text{C}$ and $+35^{\circ}\text{C}$ throughout the entire flight. These temperatures are well within the acceptable range of operation for the NIM modules and integrated circuits used in the electronics. The temperature sensor mounted in the detector sphere indicated that the inside air temperature was between -6°C and $+17^{\circ}\text{C}$ during the flight. Starting at $+17^{\circ}\text{C}$ at launch, this temperature dropped to a minimum of -6°C at 1315 UT (~ 24 km) and gradually rose to $+8^{\circ}\text{C}$ where it levelled off for the remainder of the flight. Although this temperature was below 0°C for ~ 1 hr 15 min, no malfunctions occurred which could be attributed to the $< 0^{\circ}\text{C}$ temperatures. Note, however, that this measured air temperature may not be a true indication of the temperature in the immediate NaI crystal environment. The crystal and phototubes were completely surrounded by the CPS cups, and any heat released by the phototube bleeder chains was probably retained in this small confined space, keeping the detector warmer than the air temperature outside the CPS cups. In addition, the flight orientation system worked extremely well throughout the flight. A continuous readout of the azimuth aspect showed that the modified azimuth servo system maintained the pointing direction to within the desired $\pm 3^{\circ}$ accuracy. The system responded well to all pointing commands transmitted from the ground. On this basis we can say with confidence that the look direction was known to within $\pm 3^{\circ}$ in either azimuth or elevation for the float part of the flight.

At approximately 1930 UT (after 5 hr 15 min at float altitude) an intermittent loss of the pulse height data was experienced. Coincident with this was a malfunction of the pointing system as indicated by visual ground readouts. All real time readouts during the flight (as well as a post flight review of the pertinent records) indicate that one of the two battery stacks had prematurely reached the limit of its capacity and consequently failed to provide electrical power to a number of circuits. At this point we were still able to stow the detector in its landing position, and main power was cut at 1949 UT. Data received after the first indication of this battery failure was not used in the present analysis.

Only one malfunction occurred which affected some of the data being telemetered to ground. This was a temporary loss of LER pulse height data on ascent from 1245 UT to 1400 UT (105 g/cm^2 to 4.5 g/cm^2), just prior to reaching float altitude. The problem appears to have been a loss of the gating signal which opens the LER channel to the DUAL LINEAR GATE. Since this signal also controls operation of the digital stabilizer, the gain stabilization system was inoperative during this time. With this system off the system gain could drift with temperature changes in the detector sphere and the electronics can. When the LER data returned at 1400 UT, the spectrum indicated that a gain shift had occurred. This was due to the gain stabilization circuits searching and finding a new calibration peak to lock on. Unfortunately the new peak was the 1.17 MeV Co^{60} peak rather than the 1.33 MeV Co^{60} peak initially used. The net result of this temporary malfunction, apart from the loss of LER data, was the creation of a fixed step function gain shift. At float, the stabilization circuits worked well at the new gain value. The effect of this gain shift on the detector

energy calibration was easily determined by a new post-flight calibration (see Appendix B).

3.4 Background Counting Rates

A measurement of the dependence of the various integral counting rates with atmospheric depth is important for several reasons.

1. This data indicates whether the instrument worked properly throughout the flight.

2. These rates provide a good comparison of the results obtained from both flights of the instrument.

3. An agreement in the slope of the atmospheric growth curve with previous results gives confidence that one is measuring the neutral electromagnetic component.

The counting rates (both neutral and charged particle) observed in flight 558P show the typical atmospheric depth dependence. After an initial decrease in counting rate after launch, the rates increase until a maximum is attained at $\sim 100\text{-}120 \text{ g/cm}^2$. After this maximum, the rates decrease with smaller depths, but appear to approach a non-zero value when extrapolated to zero g/cm^2 . Figures III-2 through III-4 show the dependence of the various integral counting rates on atmospheric depth as obtained on flight 558P. In these plots the depth is expressed in g/cm^2 ($1 \text{ g/cm}^2 = 0.97 \text{ mb}$). The charged particle shield rates (CPS A, CPS B, and CPS A·B) represent 9.0 second averages obtained every 80 seconds, while the LER and HER integral counting rates are 20 second averages obtained every 60 seconds. Any error bars ($\pm 1\sigma$) shown in these figures were calculated solely from sample counting statistics, $\pm (N)^{1/2}/t$. Where no error

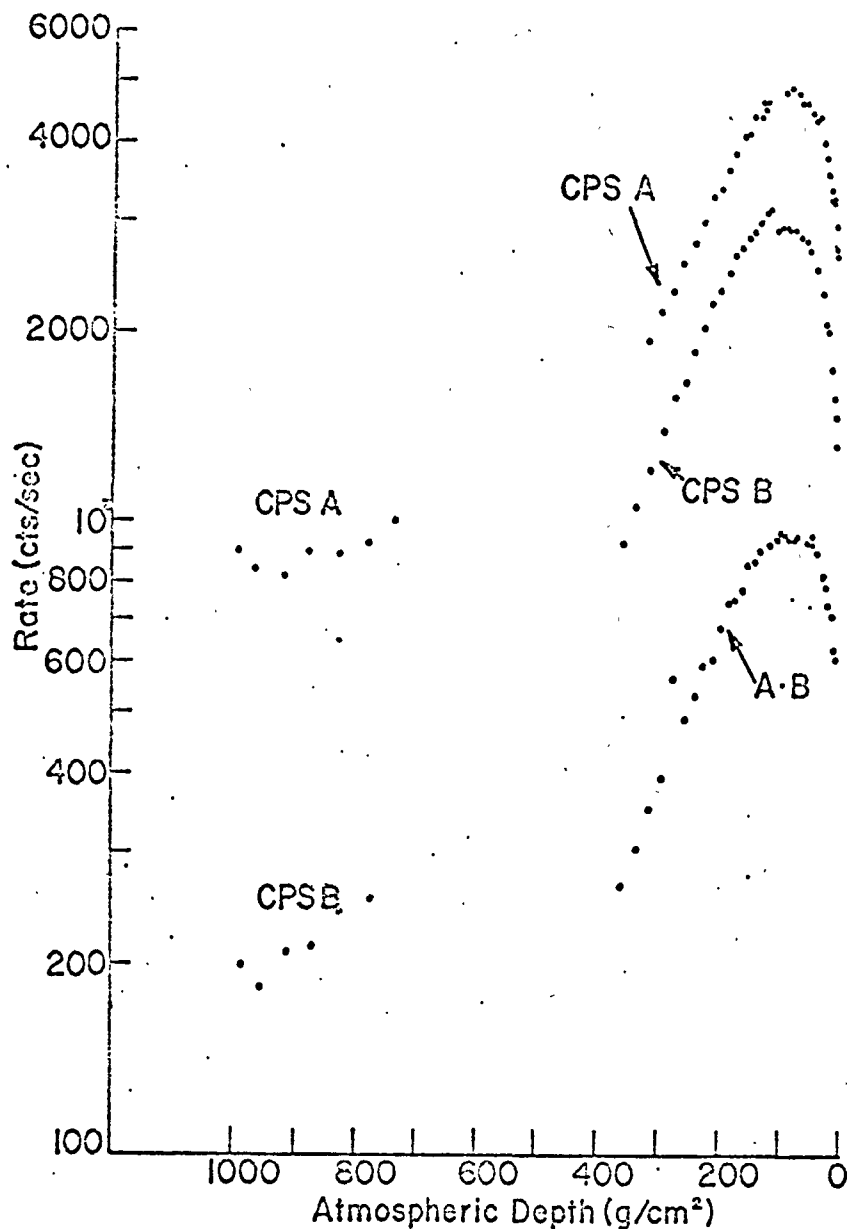


Figure III-2. Atmospheric dependence of charged particle shield counting rates. CPS A and CPS B are the individual rates; A·B is the coincidence rate between cups A and B. Data points represent 9 sec averages obtained every 80 sec. Data was lost between ~ 700 g/cm² and ~ 350 g/cm² due to a telemetry dropout.

11 1/2" ϕ x 4" NaI Spectrometer
Flight 558 P

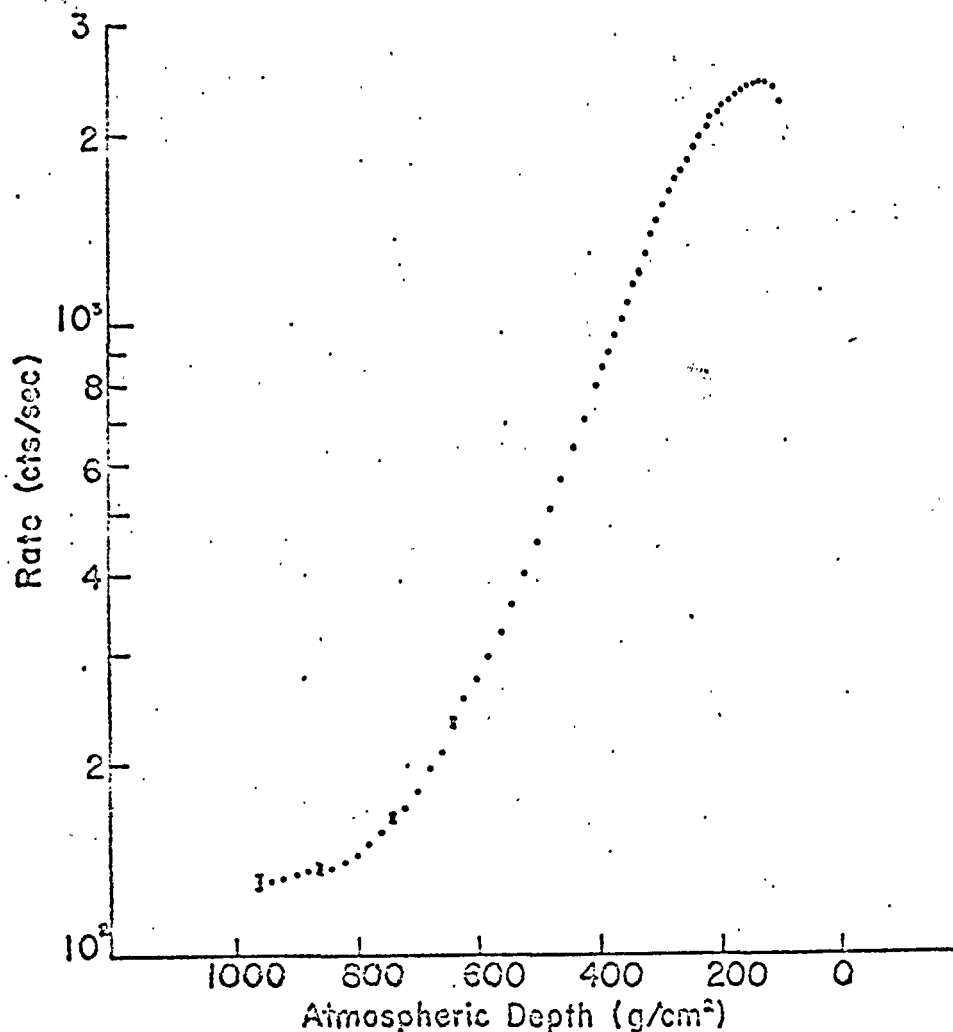


Figure III-3. Atmospheric depth dependence of integral LER counting rate. Rate includes counts from all channels of LER; the data points represent 20 sec averages and are corrected for buffer dead-time losses. Loss of LER pulse height data occurred at ~ 120 g/cm² due to a temporary electronics failure, but returned at a depth of 4 g/cm². The errors are smaller than the plotted points.

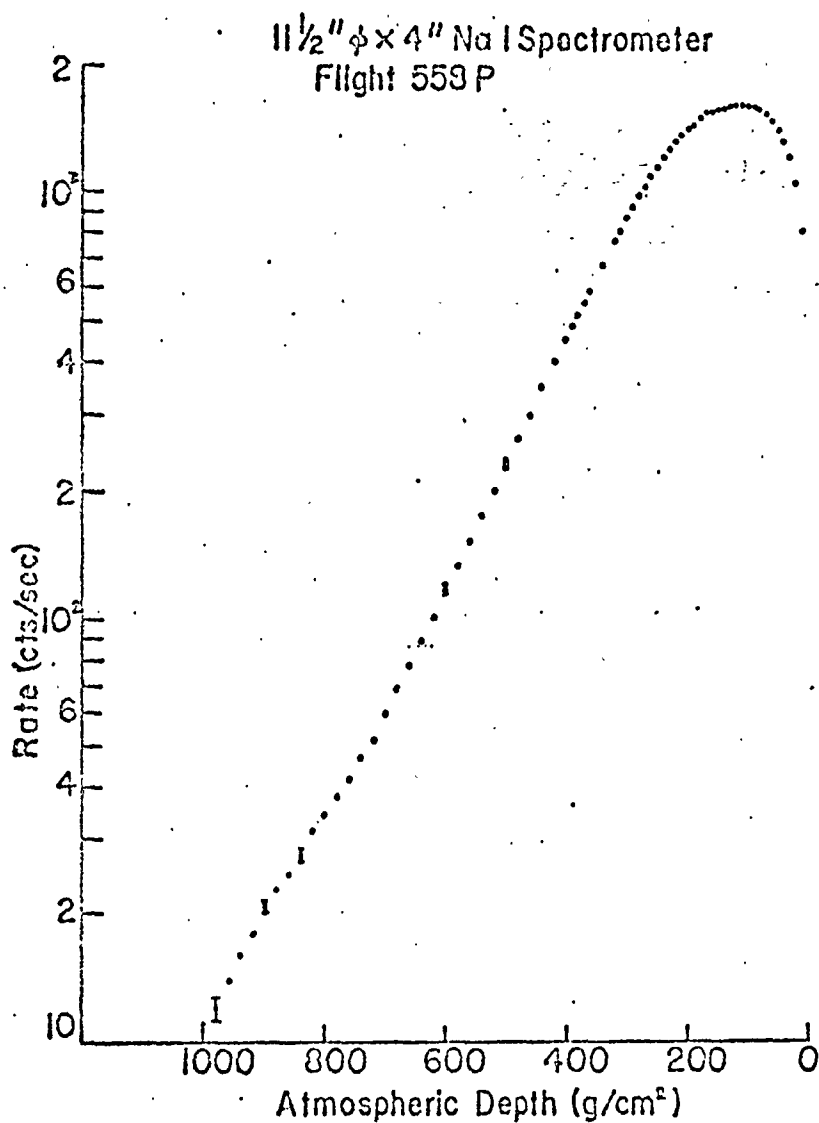


Figure III-4. Atmospheric depth dependence of integral HER counting rate. Rate includes counts from all channels of HER and is corrected for buffer deadtime losses. Errors are smaller than the plotted points except where noted by error bars.

bars are indicated, the errors are smaller than the plotted points. Note that the CPS A·B rate is a coincidence rate between CPS A and CPS B. Because of the geometry of these cups, this counting rate should be a good indicator of the through-particle rate in the central detector (the rate of those charged particles which traverse both shields and penetrate the central crystal).

The absence of CPS counting rate data from ~ 750 g/cm² to ~ 450 g/cm² resulted from an intermittent telemetry dropout problem due to a misalignment of the antenna on receiver no. 2. The multiplexed CPS counting rates were therefore unreliable during this period and have not been included here. The results for the LER and HER are counting rates obtained from the telemetered pulse height data which were not affected by the telemetry dropout problem. They have been corrected only for buffer deadtime losses. The loss of the LER data at an atmospheric depth of ~ 105 g/cm² was due to the temporary electronics failure described in Section 3.3. This data returned at a depth of ~ 4.5 g/cm². The results of Figures III-2 through III-4 indicate that the system was operating as expected and that normal qualitative results were obtained throughout the flight.

The float portion of the flight is of major interest here, since it was during this time that source observations were made. It is important to note that the normal non-source-associated fluctuations in counting rates usually observed at float altitude due to altitude changes, changes in geomagnetic latitude, and changes due to gain drifts do not present a serious drawback to the pulsar search method used on the data. This method is inherently insensitive to fluctuations of the described type unless, by chance, these fluctuations are periodic with the same period (or harmonic

of same) as the signal being searched for.

To get some indication of the typical gamma ray background spectrum observed at float altitude, Figure III-5 shows the combined LER and HER pulse height spectrums obtained by adding together all of the pulse height data obtained at float altitude (from 1447 UT to 1924 UT). These results have been corrected for deadtime losses and attenuation in the surrounding CPS cups and pressure sphere material. Assuming that the observed flux is isotropic and using an average detector geometry factor, $G_0 = 570 \text{ cm}^2$, we obtain the differential pulse height spectrum of Figure III-5. This spectrum is valid for an atmospheric depth $\sim 3.5 \text{ g/cm}^2$ and geomagnetic latitude of 40°N . In the LER, the 0.5 MeV annihilation line is the only prominent atmospheric background feature observed. The three peaks from 1.1 to 1.5 MeV are due to the two leakage lines from the Co^{60} calibration source and the K^{40} line contribution at 1.47 MeV, which is an intrinsic background feature of the large spectrometer. In the HER there are strong indications for several possible line contributions. These results, although quite interesting, are not discussed further here since they are not central to the thesis topic.

From about 1430 UT until the battery malfunction the pointing system was used to keep the Sun within the FWHM aperture of the detector. Calculations for the day of the flight indicated that the Crab-Nebula lags the Sun in meridian transit by only 33 minutes ($\sim 8^\circ$). Also, the maximum difference between the declination of the Sun and the Crab Nebula from 1430 UT to 2000 UT is only $42'$, or ~ 0.7 degree. Since the instrument was pointed to an accuracy of $\pm 3^\circ$ about the Solar direction, we can say with confidence that the Crab Nebula was in full view of the detector from

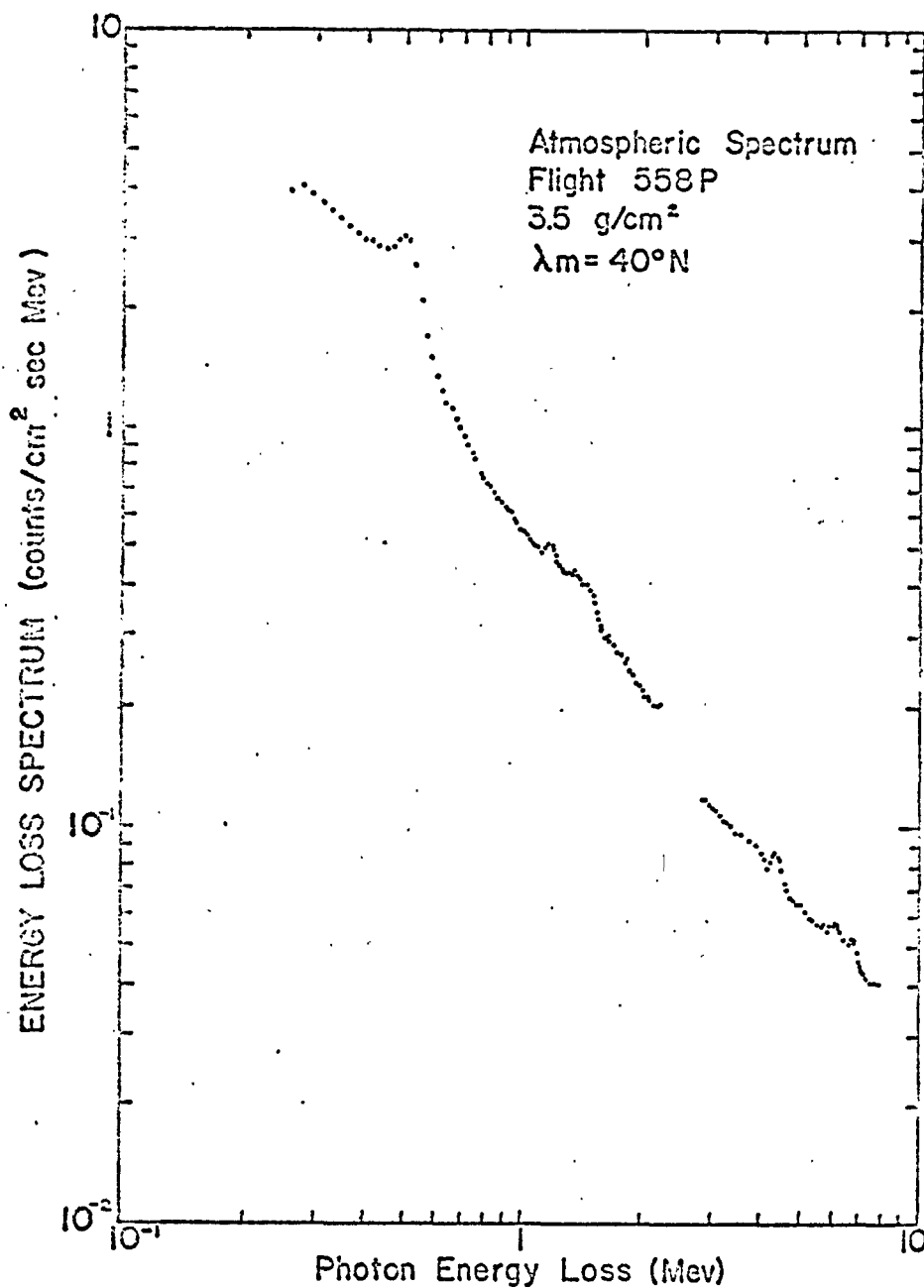


Figure III-5. Differential pulse height spectrum at 3.5 g/cm² and geomagnetic latitude 40°N measured with present spectrometer. The spectrum is corrected for deadtime losses and attenuation in the surrounding material but does not represent a photon flux as detector efficiency has not been included. The gap in spectrum is due to smearing of HER SELECT DISC threshold.

1430 UT on.

In the next section, several techniques used to search for pulsar signals are discussed. The method used in the present analysis is then described in detail.

SECTION IV

PULSAR SEARCH TECHNIQUE

4.1 Description of Analysis Methods

Basically there are three widely used techniques of time domain analysis used in pulsar searching, (1) the autocorrelation-power spectrum technique, (2) the cross-correlation method, and (3) the superposed epoch method of analysis. In this section I wish to describe each of these methods briefly, giving their advantages and disadvantages as pulsar search techniques. The details of the method used in the present work are then given.

The autocorrelation-power spectrum technique is widely used when looking for periodic signals in a set of data. Mathematically this technique is well covered in the literature (see, for example, BLACKMAN and TUKEY, 1958, and BENDAT and PIERSON, 1966). I shall describe here the standard Blackman-Tukey method of power spectral density (PSD) calculations. The method has become quite useful since the advent of large high-speed digital computers, and standard digital computational methods have been developed to handle the many computations required in the method (for example, the fast Fourier transform technique).

In this technique, a waveform (which could be a smoothly varying function, or a series of discretely occurring events) is multiplied by a time shifted version of itself over the duration of the waveform. The multiplication is done ordinate by ordinate and the sum of all these

products is taken. This process is repeated for many different time shifts (or "lag times", τ). If the normalized product at each shift is plotted versus the lag time, the resulting function is called the "autocorrelation function", R_{xx} , of the waveform or series of discrete events. The autocorrelation function of a continuous waveform $x(t)$ is defined mathematically as

$$R_{xx}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T x(t)x(t-\tau)dt$$

where $x(t-\tau)$ is the shifted waveform, τ is the lag time, and T is the length of the data record.

For use in digital computation systems, the continuous averaging process implied by the above equation is replaced by a procedure of sampling the signal every Δt seconds and summing a finite number, N , of the sample products. In this case

$$R_{xx}(\tau) = \frac{1}{N} \sum_{k=1}^N x(k\Delta t)x(k\Delta t-\tau) \quad \text{IV-1}$$

In the absence of a periodic signal in the data, $R_{xx}(\tau)$ is flat (within statistical fluctuations) except at zero lag time ($\tau = 0$) where there is always a peak. The presence of periodic signals is evidenced by peaks appearing in $R_{xx}(\tau)$ at values of τ corresponding to the periods of the components present. In a pulsar search, this calculation is performed on a set of data for a large range of τ values. In this way the data can be tested for periodicities over a large frequency range.

The power spectral density function, $G_{xx}(f)$, is found by taking the Fourier transform of $R_{xx}(\tau)$,

$$G_{xx}(f) = 2 \int_{-\infty}^{\infty} R_{xx}(\tau) e^{-i2\pi f\tau} d\tau, \quad f > 0.$$

This integral must be evaluated numerically because of the finite data record. If τ_m is the maximum value of τ chosen in the analysis, we obtain a truncated sample power spectral density function,

$$G_{xx}(f) = 4 \int_0^{\tau_m} R_{xx}(\tau) \cos 2\pi f\tau d\tau. \quad \text{IV-2}$$

(The integral of equation IV-2 is equivalent to that of the previous equation because of the evenness of $R_{xx}(\tau)$ and the odd imaginary part of the exponential).

$G_{xx}(f)$ is a measure of the power existing in different frequencies in the data. A plot of $G_{xx}(f)$ vs. f (or $1/\tau$) will exhibit peaks at the contributing frequencies, or will be flat (within statistical variations) if no periodic components exist. The peak areas in this PSD curve provide a measure of the relative contribution of different frequencies in the data. Because of the adaptability of these calculations to digital computers, the combined autocorrelation-PSD technique is quite powerful and has been used successfully for pulsar searches (see, for example, FRITZ et al., 1969).

The main advantage of this technique for pulsar searching is that it requires no knowledge or assumptions about specific pulsar emission parameters. It is a true search method. One disadvantage is that the method provides no phase or absolute timing information for a detected

periodic signal, which may be of importance in certain situations. Another disadvantage is the large amount of computer time required to make the calculations. This time is often of the order of the observation time for data taking, which, for balloon flight experiments, can be quite long (up to tens of hours).

In another version of the correlation process, the cross-correlation technique, the shifted data waveform $x(t-\tau)$ is multiplied, ordinate by ordinate, by a selected periodic "template" waveform $y(t)$, and the products summed. Mathematically this is represented by

$$R_{xy}(\tau) = \lim_{T \rightarrow \infty} \int_0^T x(t-\tau)y(t)dt, \quad \text{IV-3}$$

or in the sampling case by

$$R_{xy}(\tau) = \frac{1}{N} \sum_{k=1}^N x(k\Delta t - \tau)y(k\Delta t). \quad \text{IV-4}$$

This technique tests the similarity between the data and a selected waveform. Usually, the generation of $y(t)$ requires certain preconceptions about the pulsar emission process (BURNS and CLARK, 1969). Certain parameters in the generated waveform are adjustable, such as period, pulse width, and phase (τ). Correlation is performed for many combinations of these parameters, each being varied over its range of interest. If periodicities exist in $x(t)$, a peak will occur in $R_{xy}(\tau)$ for the proper choice of the various parameters.

This procedure can provide some information about pulse shape as well as absolute phase information, which cannot be obtained from the PSD approach. However, this

technique also has the requirement that a reference data train must be generated, which implies some assumptions about the pulsed emission (e.g. the approximate period, pulse width and shape to be expected). Also, a large amount of computer time is needed in cross-correlation calculations. For this reason the method does not appear to be as useful for the detection of unknown signals, although it is used by a number of research groups (BURNS and CLARK, 1969) as a pulsar search technique in the radio region of the spectrum.

The third technique, the superposed epoch method, is a method of synchronous signal averaging. In this method the data is superposed or overlayed in phase at a chosen frequency. If a periodic signal exists in the data with frequency equal to the frequency of superposition, a reinforcement will occur, giving an enhancement above statistical fluctuations. If no periodic signal is present, or if the signal periodicities are not equal to the superposition frequency, no reinforcement occurs, and the resulting phase plot will be statistically flat. Hence, a periodic signal is detected only when the frequency of overlap is precisely equal to the signal frequency. Note that the phase plot resulting from this method of analysis is the time-averaged phase profile of the periodic signal.

In a search for an unknown signal, this superposition process must be repeated many times using a different overlap frequency for each search. The analysis time for this method can therefore become quite long depending on the range of periods desired in the search process. However, the analysis method is easily adaptable to non-computer techniques, which is important if access to digital computing facilities is limited or if the amount of data is large and computer analysis would be costly and time consuming. As in cross-

correlation, this technique requires some pre-knowledge of the pulsar emission parameters. Specifically, the pulsar frequency and rate of change of frequency must be assumed in this method. The advantage of the method, however, is the ability to obtain absolute phase timing information and information on the time-averaged pulse profiles of the emitted radiation.

The advantages and disadvantages given for each method above were considered in choosing a search technique. The superposed epoch method was chosen for two reasons. First, it was concluded that absolute phase and pulse profile information were necessary in the present analysis. This is based on the fact that positive observations made with a non-directional instrument, such as the one flown, cannot be identified with a unique emitting source. Other information is required to pinpoint the origin of the emission. Absolute timing information and phase profile information provide this additional evidence. Observation of peaks which occur in phase with, and have the same pulse profile as the pulsed emission for NP 0532 gives strong support to the premise that the pulsed radiation is indeed coming from the Crab pulsar. The fact that the data must have a known pulse shape and that pulses must arrive at known times provides a sensitive test on the Crab origin of the emission.

The precise apparent period value and slowdown rate required in the superposed epoch analysis represents no problem in the case of the Crab pulsar, NP 0532. The barycentric period and period slowdown rate for the Crab Nebula pulsar NP 0532 are well measured, and nearly continuous observation of the optical emission by astronomy groups provides new information for updating these values. In addition,

the period value and pulse arrival times do not appear to be a function of the energy of the emitted radiation, which allows us to adopt parameters measured in the optical and X-ray regions for the present gamma ray region. A number of simultaneous observations in different energy regions (CONKLIN et al., 1969; BRADT et al., 1969) verify this energy independence of the important pulsar timing parameters (at least from the radio to X-ray bands). These parameters are thus accurately known and readily available. The knowledge of these quantities for NP 0532 eliminates the need for sweeping through a large frequency range in the search process, thereby simplifying the analysis.

The second consideration was a purely instrumental one. As discussed previously, the true search methods require a great deal of analysis time and must, in all practicality, be performed on a digital computer. At the time when our attempts at data reduction were begun, no provision existed for transferring our data into a form compatible for complete computer analysis. A good deal of electronics interface hardware would have had to be constructed to perform this task. On the other hand the superposed epoch analysis lends itself more easily to a non-computer approach using readily available laboratory equipment (plus construction of relatively simple interface equipment).

Based on these two considerations, (1) the necessity for obtaining absolute timing and pulse profile information, and (2) the availability and simplicity of instrumentation required for data analysis, the superposed epoch analysis technique was the obvious choice for the pulsar search method.

4.2 Instrumentation for Pulsar Search

The instrumentation for the present analysis was very similar to that used by NATHER et al. (1969), BOYNTON et al. (1969), and DUTHIE and MURDIN (1971). A block diagram of this electronics instrumentation is shown in Figure IV-1. The electronics is needed to generate an overlap frequency which is synchronized to the WWV signals recorded on the magnetic tape. This frequency and signals derived from it are used to control the superposition of the data. The WWV signal thus becomes the basic time standard for the analysis.

To use the long-term timing accuracy of the WWV signal, and obtain a clean timing signal to drive the frequency synthesizer, an 80 kHz signal was recorded on one channel of the magnetic tape in synchronism with the WWV timing markers. This was done in the laboratory after the flight and was accomplished by forcing 80,000 cycles of a timing oscillator to fit between each 1 Hz marker on the tape. Synchronism between the oscillator and the markers was obtained by dividing the 80 kHz signal by 80,000 and maintaining the resulting 1 Hz signal at a constant phase with respect to the 1 Hz WWV markers. The maximum synchronization error experienced in this process was ± 1 ms. Note that this is a non-accumulative error. The majority of the time this error was held below ± 0.5 ms. Sections of the tape where this error was greater than 1 ms were not used in the analysis. This clean 80 kHz signal was used to drive a phase-locked-loop (PLL) which generated two signals, a duplicate 80 kHz signal and a 10 MHz signal. The 10 MHz signal became the base frequency for use in the frequency synthesizer. The operation of the PLL assured that the synthesizer was synchronized to the WWV signal and therefore has good long-term time stability.

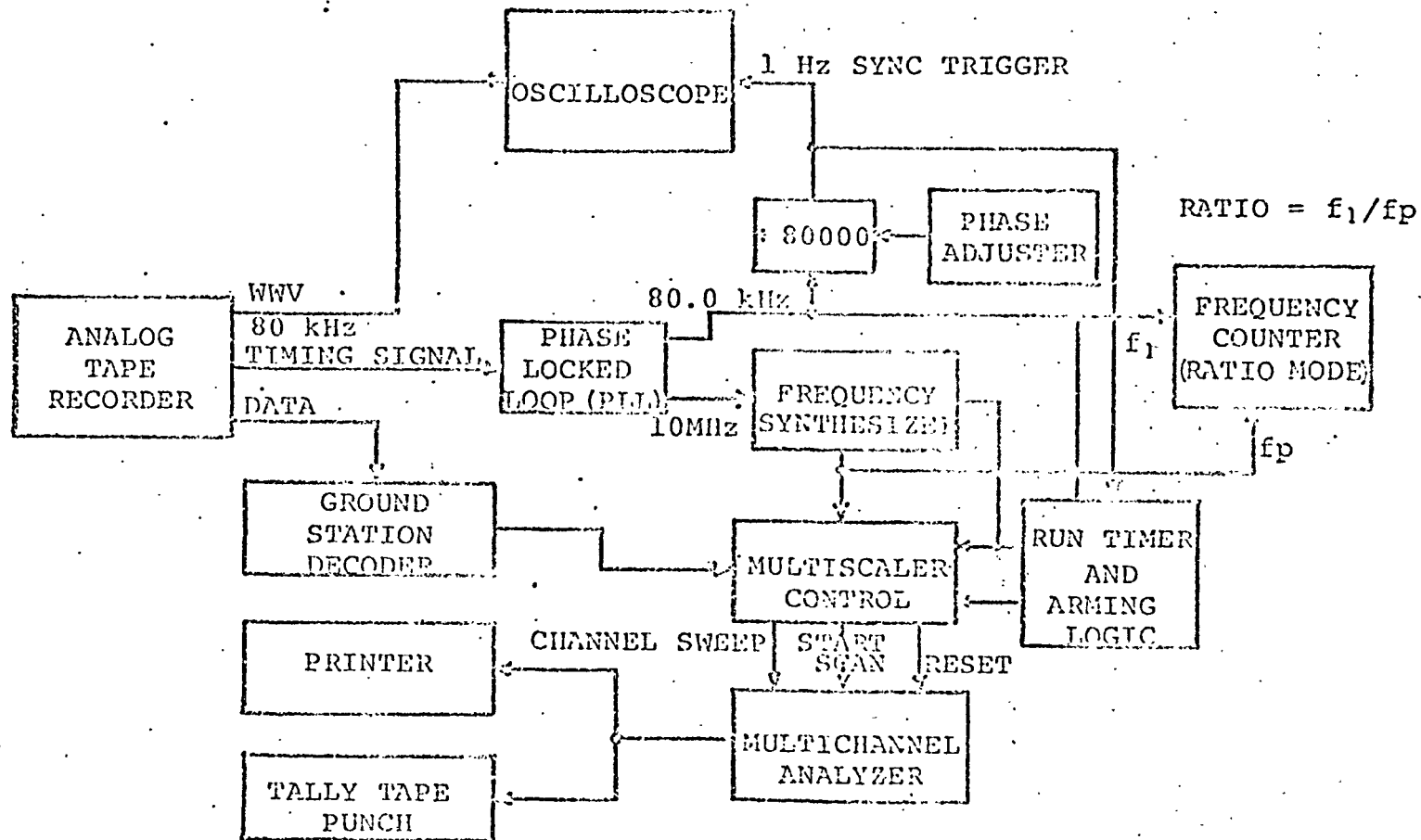


Figure IV-1. Diagram of Pulsar Search Equipment

The digital frequency synthesizer (designed and built at UNH) could be adjusted over the period range from 0.0001 ms to 99.9999 ms in increments of 0.0001 ms (100 ns). The synthesized frequency was adjusted to most closely match the predicted apparent period of the pulsar, and controlled the recycling operation of a multichannel analyzer operating in the multiscaler mode. The synthesizer also generated a signal to advance channels on the analyzer at a 1 ms/channel sweep rate. The recycling process was repeated every period; thus one 34-channel analyzer scan corresponded to one pulsar cycle.

The electronics included provisions for synchronizing the start of a multiscaler scan to a chosen second of time. This could be done to an uncertainty of ± 1 ms maximum. This provided knowledge of the absolute arrival times for the resulting superposition phase plots. This was achieved by phase-aligning (with the PHASE ADJUSTER circuit of Figure IV-1) a synthesized 1 Hz signal to the WWV markers as they were played back off the tape. The start of a run was aligned to be 3 ms before a given WWV marker, and this constant phase offset was maintained for all the runs.

For reasons discussed in the next section, the analysis was subdivided into 32 runs, the shortest being 100 sec long and the longest, 800 sec long. A typical run would proceed as follows. First, the synthesized 1 Hz signal was brought into a fixed -3.0 ms phase offset with respect to the WWV signal from the magnetic tape. This could be done to an error of ± 0.2 ms (see Appendix F). This phase alignment was monitored during each run. The next step was to start the run at a precisely known absolute time. This was done by arming the synthesizer just prior to the second marker chosen to be the starting time of the run. The next

1 Hz trigger pulse then initiated the run, thus synchronizing the start of the multiscaler sweep process to a known absolute time. The run was electronically timed by counting the number of 1 Hz trigger pulses occurring after the start of the run. When a preset count was reached the synthesizer was automatically disabled and the run ended.

The contents of the multichannel analyzer was read out on punched paper tape and redundantly printed out on paper tape for a quick visual check of the data. The data on the punched paper tape were then converted to computer cards as input to the computer program which performed the final data analysis.

4.3 Subdivision of Data and Final Phase Alignment

The superposed epoch method of analysis requires very precise synchronization between the artificial synthesizer period and the pulsar signal. Since the multiscaler channel advance rate is 1 ms/channel for the present case, this precision must be good enough to maintain any accumulative phase drift to a value less than 1 ms during a data run. When this condition is met, no observable time drifting of the data signals occurs. If the phase drift exceeds 1 ms, data smearing will occur in the final phase diagrams. This effect, if large enough, could reduce peak signals to a value below background fluctuations.

This precise synchronization presented a problem in the present analysis because the synthesizer could not be adjusted in small enough period increments to permit continuous tracking of the pulsar period throughout the data integration time. In Appendix F it is shown that for the 16,739 sec data interval of the present analysis, the period

synchronization must be maintained to an accuracy of $\lesssim 2$ ns/period in one long run to keep the phase drift $\lesssim 1$ ms. However, the frequency synthesizer could only increment the periods in steps of 100 ns. Thus, the exact apparent pulsar period at a given time could not be synthesized. In addition, the expected apparent pulsar period for NP 0532 varies throughout the data interval (see Appendix E). Calculations for the interval used here showed that the apparent period for NP 0532 varied from 33.112301 ms at $14^{\text{h}} 32^{\text{m}} 01^{\text{s}}$ UT to 33.112338 ms at $19^{\text{h}} 11^{\text{m}} 00^{\text{s}}$ UT on June 7, 1970 (a change of 37 ns). It was impossible to track these period changes as would be required in one long run of the data.

The problem was eliminated by subdividing the data into 32 runs, each of short integration time ($\lesssim 800$ s each). The same synthesized period value was used for all runs, $P_{\text{syn}} = 33.112300 \pm 0.000005$ ms. This was the closest value to the true expected period that could be generated in the synthesizer. Note that the difference between the generated and expected period varies from +1 ns to +38 ns over the data interval. At no time was the period error larger than 38 ns. Using equation F-1 of Appendix F with $\epsilon_p = 38$ ns and $P = 33.112300$ ms, we find that in order to keep the phase drift $\lesssim 1$ ms in any run, the integration time of the run must be $\lesssim 950$ s. By keeping the accumulation time of each run $\lesssim 800$ s, we were assured that the results obtained for each run were the same as would have been obtained if the data had been superposed at the exact expected pulsar period.

The data from the multiscaler analysis therefore consisted of 32 phase diagrams which had to be superposed in phase to obtain the final composite phase diagram. It is in this final synchronization process that the overall

timing accuracy is recovered. From a knowledge of the expected apparent period versus time and the starting times of each run, it was possible to calculate and assign a pulsar phase to the start of each run. This calculation was made to the nearest multiscaler channel (1 ms). This knowledge of the position in pulsar phase of each channel of each run enabled the runs to be phase-aligned and added to each other. A computer program was written to perform this superposition of the 32 runs. The apparent pulsar period drift was included in the calculation of the starting time phases. This technique successfully recovered the tracking accuracy needed in superposing the data.

Since timing accuracy and precise synchronization are of great importance in the superposition method, it is important to consider the errors involved in these quantities for the present analysis. Appendix F is devoted to this task. In addition, Appendix E contains the calculations of the expected period changes for the day of the flight with comments on the errors in this quantity. These period changes were used in the final phase aligning procedure performed on the data by the computer program.

In the next section the results of using the superposition analysis to search for gamma ray pulsations from NP 0532 are presented.

SECTION V

RESULTS OF PULSAR ANALYSIS

5.1 LER (250 keV - 2.3 MeV)

An initial analysis using the superposed epoch technique was performed on one integral energy band extending from 250 keV to 2.3 MeV. One large band was chosen for the first look at the data to obtain a large number of counts, which would give good counting statistics and increase our ability to detect small signals above the expected large background. Data from the float portion of flight 558P was chosen for the analysis. Out of this total time interval, 1.2×10^4 sec of usable data, spanning 1.67×10^4 sec from $14^h 32^m 01^s$ to $19^h 11^m 00^s$, was analyzed for a pulsed contribution from NP 0532.

The analysis was repeatedly performed on the same set of data, each time using a new period in the computer program. The final set of phase diagrams were then scanned to look for any significant peaks. The final results for the LER data at two selected overlap frequencies are shown in Figure V-1. Figure V-1a shows the phase plot obtained when the data was superposed at the expected apparent pulsar period. As discussed in Appendix F, 2 ms wide phase bins were chosen for the final plots due to the ± 1 ms time-of-arrival uncertainty. In Figure V-1b the data was superposed at a period 80 ns higher than that expected for NP 0532 for the day of the flight. The dashed line is the average number of counts per bin, $634,011 \pm 199$ counts, calculated

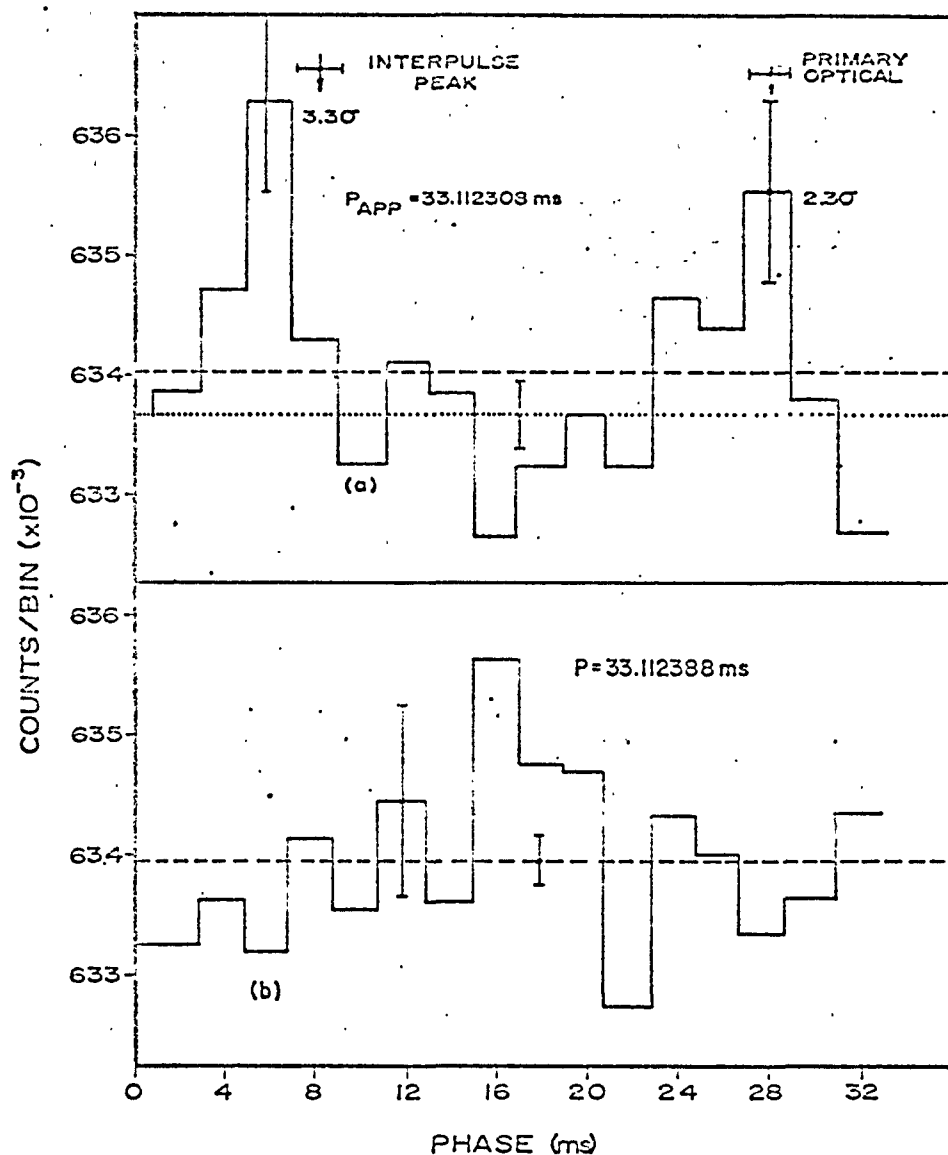


Figure V-1. (a) 2 ms/bin phase diagram of LER data (250 keV - 2.3 MeV) superposed at expected apparent period of NP 0532 for epoch of flight (33.112308 ms at 15 h 50 m 30 s UT). Dashed line is the average of all data points; the dotted line is the mean value of bins 5-13 inclusive. Error bars are $\pm 1\sigma$ deviations based solely on counting statistics. (b) Similar phase diagram for LER data superposed at a period 80 nsec higher than the expected apparent period of NP 0532.

using the contribution from all the bins. The error bars shown ($\pm 1\sigma$) are based solely on counting statistics (as are all the error bars given in the figures of this section). Two pronounced peaks (3.3σ and 2.3σ above background respectively) separated by 20 ± 2 ms appear in the data. The error bars on each peak indicate the counting error ($\sigma = (\text{AVE})^{1/2} = 796$ counts/bin) for a single bin of the data. Also indicated in the graph are the expected absolute main and interpulse arrival times for the optical radiation from NP 0532, provided by Dr. C. Papaliolios (Harvard University). The arrival times of the two peaks agree quite well with the expected arrival times for emission from NP 0532. On this basis, the first peak has been identified with the interpulse and the second with the main pulse. These identifications are also aided by the peak shapes. The first peak is the wider and more intense of the two. The narrowness of the second peak ($\lesssim 2$ ms) helped to identify it as the main pulse. These qualitative features are similar to those observed by HILLIER et al. (1970) in the energy region from 600 keV to 9 MeV, and to the pulse profiles observed in the soft and hard X-ray regions of the pulsed spectrum of NP 0532 (see, for example, BRADT et al., 1969, and SMATHERS et al., 1971).

The particular choice of starting time for the present analysis caused the interpulse peak to appear first in the phase diagram, although it is customary to see the main pulse leading in most phase profile diagrams. The pulse separation is defined as the time between the peak intensities of the pulses when the main pulse leads in the phase diagram. Hence, the observed peak separation of 20 ± 2 ms in the present plot implies a 13 ± 2 ms peak separation, in good agreement with the results obtained for the optical (LYNDS et al., 1969) and X-ray emission from NP 0532

(for example, RAPPAPORT et al., 1971, and BRINI et al., 1971).

Since the observed effect is quite small, statistical tests were performed on the data to test our confidence that a pulsed contribution had been seen. A chi-square (χ^2) statistical analysis (EVANS, p. 777) was carried out to test whether the fluctuations observed in the data could be explained by purely statistical variations. The data was tested against a model in which there was a constant number of counts in each bin equal to the average (in other words, no pulsed contribution, but merely a constant background counting rate). This χ^2 test was performed on each of the final phase plots resulting in a graph of χ^2 versus overlap period. This method has been used by a number of groups to search for the precise pulsation period of NP 0532 (notably BOLDT et al., 1969 and DEERENBERG and BLEEKER, 1971).

Results for the present experiment were obtained over a range of test periods which included the expected apparent period for NP 0532 and are given in Figure V-2. In the absence of a pulsed contribution in the data, or if the overlap period is not equal to the actual period of pulsation, the resulting χ^2 vs. period distribution should be flat (structureless). Large values of χ^2 , corresponding to a bad fit of the data, indicate some sort of non-random component in the data. The distribution for the present experiment shows a peak in a narrow period range which includes the period value expected for NP 0532 for the epoch of observation. The worst χ^2 value (30.7 at $P = 33.112312$ ms) is greater than those obtained in $\geq 98\%$ of distributions generated randomly for 15 degrees of freedom. This can be interpreted to mean that we are $\geq 98\%$ confident that a non-random effect has been observed in the data. In no other region of

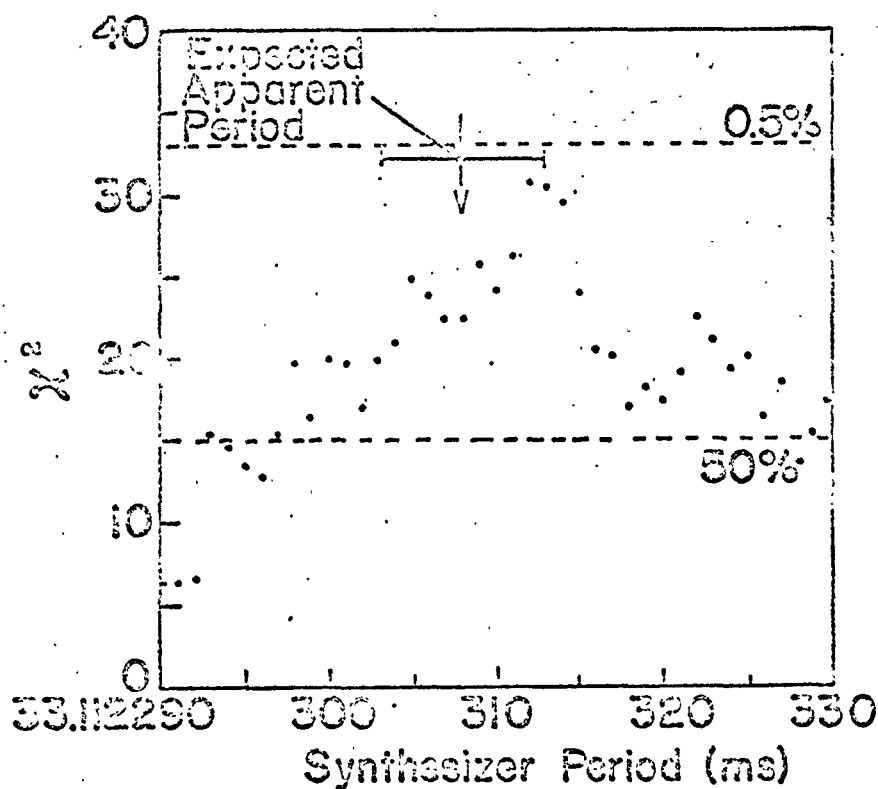


Figure V-2. χ^2 distribution for the hypothesis of a random distribution of events for 15 degrees of freedom as a function of superposition period. The error bars on the expected period arrow indicate the uncertainty in the knowledge of the apparent pulsar period of NP 0532..

test periods do we see a peak in the χ^2 of this type. This χ^2 distribution gives further support to the existence of a positive pulsed contribution in the data. This result, by itself, is not conclusive proof of the pulsation from NP 0532 but only substantiates the evidence seen in the profile phase plots.

Although the peak χ^2 value occurs at a period value not precisely coincident with the expected apparent pulsar period, the difference is within the error in our knowledge of that period (indicated by the error bars in Figure V-2). An inspection of the phase plots for any of the synthesizer period values within the peak region shows only minor differences in the resulting peak amplitudes and pulse shapes. As the synthesizer period gets further away from the expected pulsar period, the double peak profile characteristic of NP 0532 begins to disappear and eventually is masked by statistical background fluctuations.

We have checked to make sure that the peaks were not accidentally produced by some electronics anomaly or by the method of superposing the 32 runs. To do this, the entire analysis was repeated at a test period of $P = 33.113300$ ms. This included repeating each of the 32 multiscaler runs at this period. This period value was chosen because it was sufficiently different from the expected pulsar period to make the test and was a value that could be set in the frequency synthesizer. The final phase diagram for this analysis showed no peaks which coincided with the pulse arrival times for NP 0532 or which deviated by more than $\pm 2\sigma$ from the average value per bin. However, the χ^2 distribution obtained by repeating the final phase alignment at a number of test period values showed a slight increase in the region around the period 33.113300 ms. However, the

effect was not nearly as large an effect as was observed at the expected pulsar period. The results of this test showed that no electronics anomaly existed which could produce the double peak in the phase plot or as large a peak as seen in the χ^2 distribution for the actual pulsar search data. It thus appears that the peak in the χ^2 distribution for the actual pulsar search runs is a real effect and not an anomaly produced by the electronics or the analysis method. In any case, we have used the χ^2 distribution only as supporting evidence for, not proof of, a non-random pulsed contribution in the data.

To calculate the pulsed contribution it was assumed that the pulse shapes do not change drastically from those observed in the hard X-ray region (see, for example, SMATHERS et al., 1971). Under this assumption, phase bins 5 to 13 were chosen as the non-pulsed background region, yielding a value of $633,670 \pm 265$ counts per bin as the average non-pulsed background. Similarly, bins 1 to 4 inclusive were designated as the interpulse peak region and bin 14 as the main peak region. On this basis the interpulse peak contains 4494 ± 2251 counts and the main peak contains 1845 ± 1126 counts, which implies a total pulsed count (main + interpulse) of 6339 ± 2517 counts and a ratio of interpulse intensity to main pulse intensity of 2.4 ± 1.9 .

This measured number of counts must be corrected to the top of the atmosphere, which required the following corrections to the data:

(1) Corrections were made for electronics deadtime losses. These included buffer losses in the flight electronics as well as multiscaler deadtime losses obtained in the pulsar analysis.

(2) Corrections were made for the attenuation of material surrounding the central spectrometer; namely, the 1 g/cm^2 thick charged particle shield, the pressure sphere ($\sim 0.2 \text{ g/cm}^2$ thick), and the foam insulation surrounding the pressure sphere.

(3) A correction was made for atmospheric attenuation. In calculating the third correction, the counts at a depth of 3.5 g/cm^2 were corrected to zero g/cm^2 atmospheric depth assuming that the detector was positioned at an average zenith angle (from the vertical) of $\sim 30^\circ$ throughout the data interval. (This angle actually varied from about 45° to 12° during the interval). The atmospheric thickness between NP 0532 and the detector was obtained from the calculations of PRESSLY (1953) for an atmospheric depth of 3.5 g/cm^2 ($\sim 38.2 \text{ km}$) and zenith angle $\xi = 30^\circ$. This thickness, $\sim 4 \text{ g/cm}^2$, was then used in the gamma ray attenuation calculation. The atmospheric attenuation was calculated for a photon energy of $\sim 620 \text{ KeV}$, which is the weighted mean energy of the LER region using an E_γ^{-2} weighting function.

The time-averaged pulsed photon flux was obtained from the equation:

$$\bar{F}(\text{LER}) = \frac{N_{\text{obs}} f_{\text{corr}}}{\bar{P}_1 A T} \text{ photons cm}^{-2} \text{ sec}^{-1}, \quad \text{V-1}$$

where N_{obs} = the sum of the observed main and interpulse counts,

f_{corr} = factor which corrects data to zero g/cm^2 atmospheric depth (1.60),

$\bar{P}_1$ = average weighted detection efficiency for photons in the LER (see Appendix C),

A = effective spectrometer area presented to NP 0532 during data interval ($\sim 670 \text{ cm}^2$),

and T = total data accumulation time used in pulsar analysis (12,000 sec).

Using equation V-1 the time-averaged pulsed flux from 250 keV to 2.3 MeV was found to be

$$\bar{F}(\text{LER}) = (1.44 \pm 0.57) \times 10^{-3} \text{ photons cm}^{-2} \text{ sec}^{-1}.$$

For comparison with other measurements of NP 0532 it is convenient to convert this photon flux into an energy flux, $I(E)$ ($\text{keV/cm}^2 \text{ sec keV}$) valid in this energy interval. At this time no spectral information had been obtained from the data. No spectral shape was assumed in making this calculation. Instead, an average pulsed power, I_{AVE} , which would give the observed integral pulsed photon flux in the LER energy region, was calculated. The average energy flux is defined by

$$\bar{F}(\text{LER}) = \int_{E_1}^{E_2} (I(E)/E) dE = I_{\text{AVE}} \int_{E_1}^{E_2} dE/E,$$

where E_1 and E_2 are the lower and upper threshold energies respectively for the LER.

Thus,

$$I_{\text{AVE}}(\text{LER}) = \frac{\bar{F}(\text{LER})}{\ln(E_2/E_1)}. \quad \text{V-2}$$

From equation V-2 we obtained

$$I_{\text{AVE}}(\text{LER}) = (6.49 \pm 2.57) \times 10^{-4} \text{ keV cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1}.$$

These results, valid in the energy region 250 keV - 2.3 MeV were published by the author and co-workers (ORWIG et al., 1971).

5.2 Spectral Results for Energies > 250 keV

Following this initial success with the measurement of a positive contribution in one energy window, it was decided to subdivide this energy interval in an attempt to obtain spectral information. Also, the search was extended to energies > 2.3 MeV using the HER pulse height data obtained on the same flight. The LER was therefore subdivided into two separate energy bins, LER A (250 keV - 725 keV) and LER B (725 keV - 2.3 MeV). The division was made at an energy of 725 keV for two reasons: (1) subdivision at this energy would yield approximately equal counting rates for LER A and LER B, resulting in similar statistical accuracy for each energy bin, and (2) subdivision at this energy was easy to accomplish instrumentally with the pulse height decoding electronics. LER A thus represented channels 0 to 63 inclusive of the LER pulse height spectrum, while LER B consisted of channels 64 to 250. The HER pulse height information was treated as an integral rate above 2.3 MeV. With this subdivision, three spectral points could be obtained in the region above 250 keV. In addition to these energy intervals, a small window about the 511 keV annihilation line region was also chosen to search for an enhanced pulsed contribution due to annihilation radiation. This window extended from 450 keV to 550 keV (the full width at one-tenth maximum points of the photopeak response curve for 511 keV radiation.)

A complete superposition analysis, exactly similar to that described above for the LER search, was repeated for each of the four separate energy intervals. Figures V-3 through V-6 show the phase diagrams obtained at a synthesized period of 33.112312 ms and at an off-period value for each

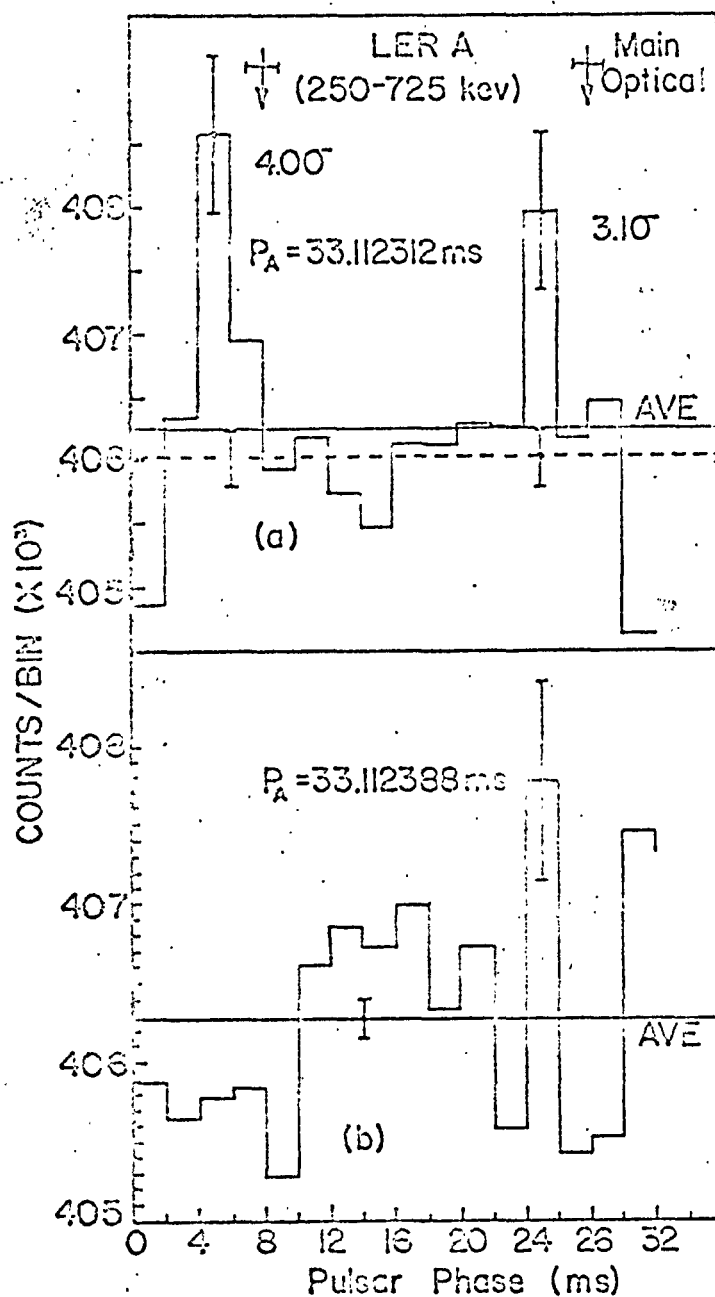


Figure V-3. (a) 2 ms/bin phase diagram for LER A energy bin (250 keV - 725 keV), superposed at apparent period of 33.112312 ms. Solid line (AVE) is the average of all data points; the dashed line is the mean of bins 5-12 inclusive. Error bars ($\pm 1\sigma$) on dashed line give the error in the non-pulsed background due to counting statistics. Error bars ($\pm 1\sigma$) on peaks are single channel errors due to counting statistics. Arrows indicate optical pulse arrival locations. (b) Similar phase diagram for an off-period superposition. Error bars are $\pm 1\sigma$ deviations in AVE due to counting statistics.

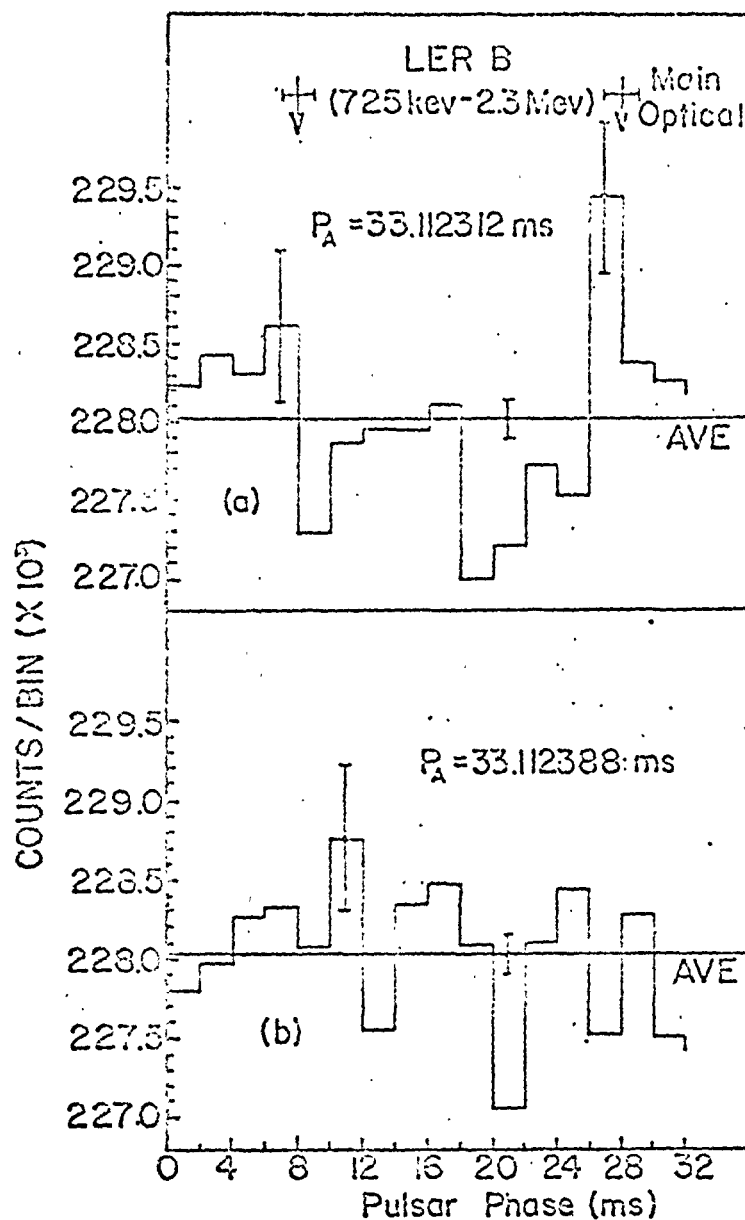


Figure V-4. (a) 2 ms/bin phase diagram for LER B energy bin (725 keV - 2.3 MeV) superposed at apparent period of 33.112312 ms. Solid line (AVE) is average of all data points. Error bars are $\pm 1\sigma$ deviations in AVE and single channel counts due to counting statistics. Arrows indicate optical pulse arrival locations. (b) Similar phase diagram for an off-period superposition.

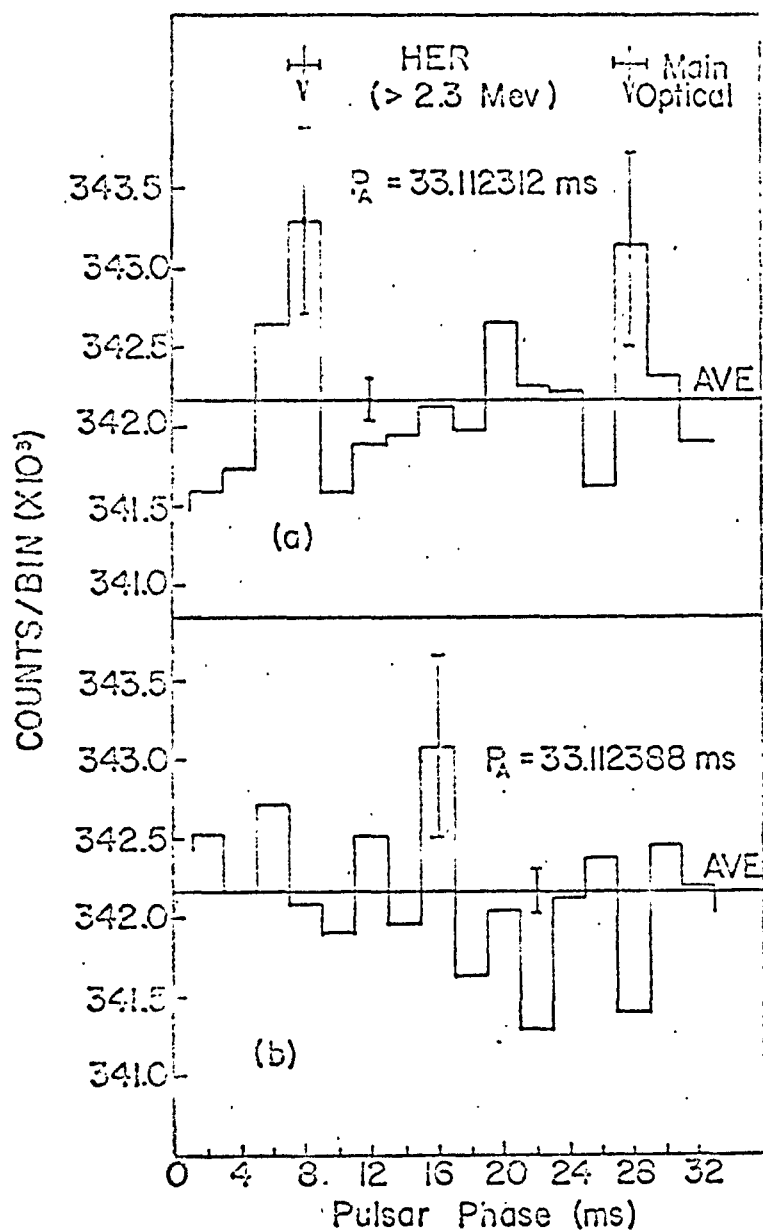


Figure V-5. (a) 2 ms/bin phase diagram for HER energy bin (> 2.3 MeV) superposed at apparent period of 33.112312 ms. Solid line (AVE) is average of all data points. Error bars are $\pm 1\sigma$ deviations in AVE and single channel counts due to counting statistics. Arrows indicate optical pulse arrival locations. (b) Similar phase diagram for an off-period superposition.

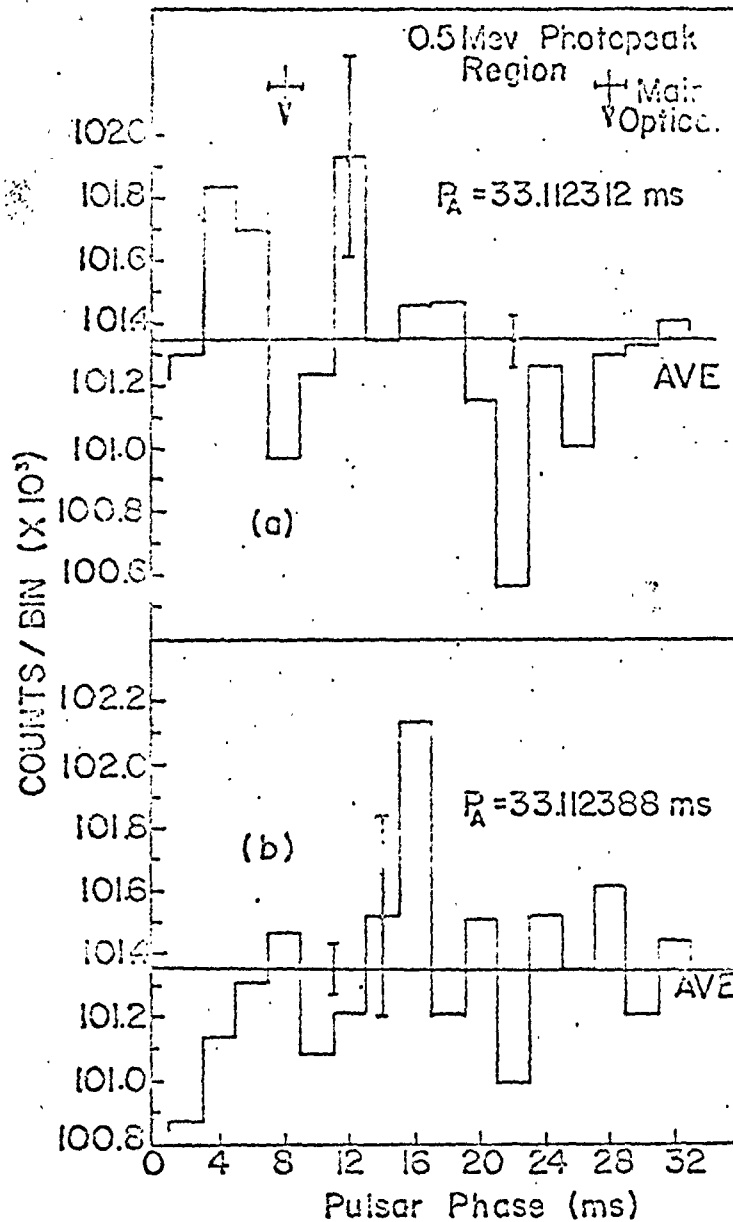


Figure V-6. (a) 2 ms/bin phase diagram for 0.5 MeV photopulse region (450 keV - 550 keV) superposed at apparent period of 33.112312 ms. Solid line (AVE) is average of all data points. Error bars are $\pm 1\sigma$ deviations in AVE and single channel counts due to counting statistics. Arrows indicate optical pulse arrival locations. (b) Similar phase diagram for an off-period superposition.

energy bin. Figure V-7 contains the χ^2 vs. test period distribution obtained for each of the four energy intervals. To provide a consistent approach to the analysis of these energy intervals, the phase diagrams at a period of 33.112312 ms were chosen as the most representative plots. Phase plots at this particular period value were picked because, (1) the peak in the LER χ^2 distribution occurred at this period, and (2) within the error of our period calculations, this value is equivalent to the apparent period of NP 0532.

What is immediately noticeable from viewing the complete set of phase diagrams (not shown here) for these subdivided energy intervals is the high degree of variability in the phase profiles, except for the LER A data. This is a result of the decrease in signal to background for the LER B, 0.5 MeV and HER intervals. This is evidenced by the fact that the phase diagrams vary a great deal depending on how the channel grouping was performed to obtain the 2 ms/bin phase plots. Hence, the pulse shape information is much less definitive than obtained for the integral LER window.

As Figure V-7 shows, there is no strong evidence in the χ^2 distribution for nonstatistical fluctuations at the expected apparent pulsar period for the LER B, HER, or 0.5 MeV data. In the distribution for LER A, however, a peak does appear near the expected pulsar period. The peak has its maximum χ^2 value at a period of 33.112312 ms, in agreement with the previous results for the LER. The χ^2 value of 35.6 at $P = 33.112312$ ms represents a $\ll 0.1\%$ chance that the LER A data could be explained by normal statistical fluctuations. This indication is confirmed by the phase diagram which shows clearly the two peaks, a 4.0σ interpulse and a 3.1σ main pulse. Although the absolute time alignment is not quite as good as the LER case (the peaks appear to be

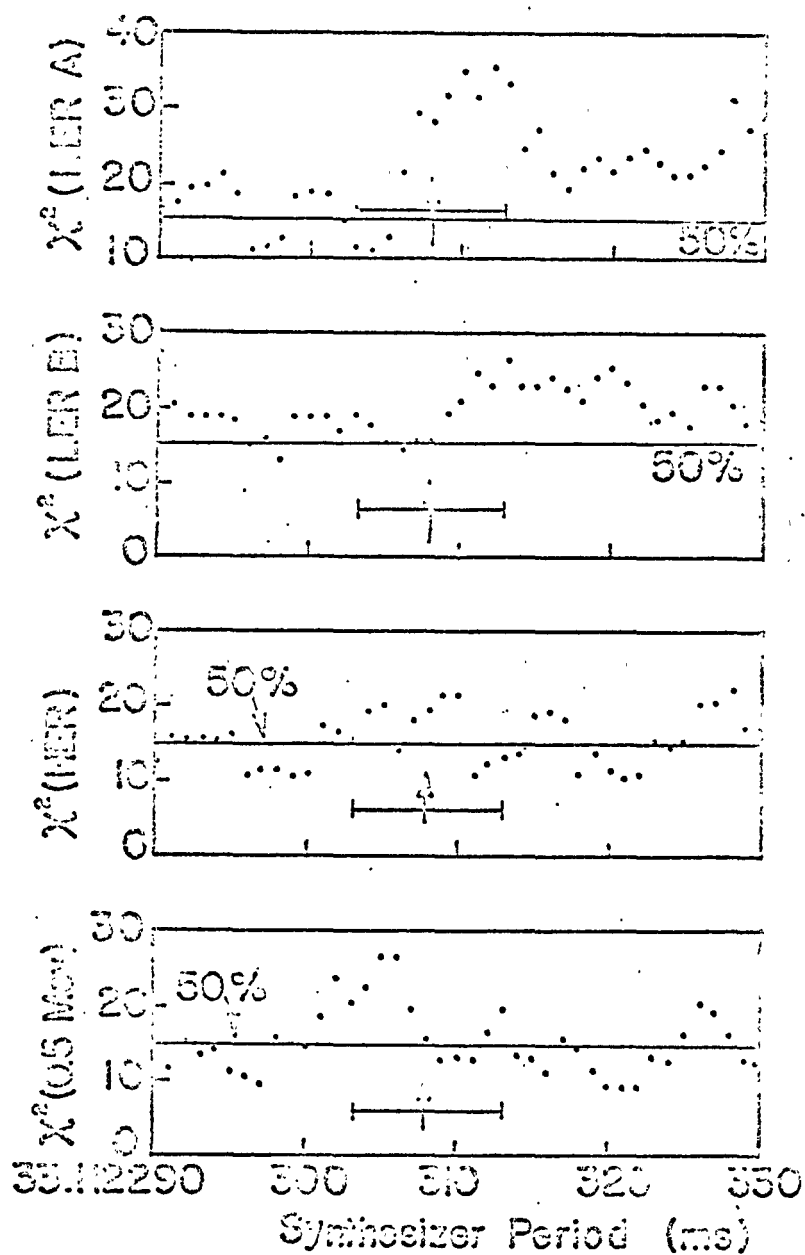


Figure V-7. χ^2 distributions obtained for LER A, LER B, HER, and 0.5 MeV energy bins on the hypothesis of a random distribution of events for 15 degrees of freedom (50% line). Note the difference in vertical scale on the LER A plot. A χ^2 of 30 represents $\approx 2\%$ chance that the data can be explained by random events. The error bars on the expected apparent period arrow for NP 0532 indicate the uncertainty in the knowledge of this quantity.

shifted 2 ms toward earlier times), the pulse separation is still found to be 13 ± 2 ms.

From the LER A phase plot, channels 5 to 12 inclusive were chosen as the non-pulsed background region. Bins 1-4 were selected as the interpulse region, with bin 13 being the main pulse region. These choices for the peak regions gave 2657 ± 1802 counts and 1960 ± 901 counts for the interpulse and main pulse respectively. The total pulsed area is 4617 ± 2015 counts and the intensity ratio of interpulse to main pulse is calculated to be 1.36 ± 1.11 . Using equations analagous to V-1 and V-2 (with $\bar{P}_2 = 0.90$ replacing $\bar{P}_1$, $f_{\text{corr}} = 1.83$, $N_{\text{obs}} = 4617 \pm 2015$ counts, and the other parameters the same), the time-averaged pulsed photon flux from 250-725 keV was found to be

$$\bar{F}(\text{LER A}) = (1.20 \pm 0.52) \times 10^{-3} \text{ photons cm}^{-2} \text{ sec}^{-1}$$

and the average pulsed power,

$$I_{\text{AVE}}(\text{LER A}) = (1.14 \pm 0.50) \times 10^{-3} \text{ keV cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1}.$$

These results are listed in Table V-1.

Although the LER B phase plot contains some indication of a small contribution at the proper absolute times, there is no contribution above 2σ in the entire expected interpulse region. The χ^2 distribution does not indicate the presence of any unusual fluctuations. Also, the sum of the contributions in the expected peak regions is less than a 2σ effect. Consequently, the results for this energy bin are reported as upper limit fluxes.

The 2σ upper limit flux valid at zero atmospheric depth is given by

$$F \lesssim \frac{2.8}{A \bar{P}_3 T} (nfN_{\text{AVE}})^{1/2} \exp(\mu \bar{d}) \text{ photons cm}^{-2} \text{ sec}^{-1}, \quad \text{V-3}$$

where F = the upper limit photon flux in the LER B energy interval, A = the effective crystal area facing the source, $\bar{P}_3$ = the average detection probability for LER B (0.68 from Appendix C), T = the length of the data interval (12,000 sec), n = the number of phase bins chosen as the total peak region (5), N_{AVE} = the average number of counts/bin from the LER B phase diagram at $P = 33.112312$ ms, and f = the correction factor for deadtime losses and attenuation in the surrounding material (1.2). The term $e^{\mu \bar{d}}$ corrects the upper limit obtained at 3.5 g/cm^2 atmospheric depth to the top of the atmosphere. Here, μ is the attenuation coefficient ($0.057 \text{ cm}^2/\text{g}$) for photons of energy equal to the mean energy of the LER B interval ($\sim 1.2 \text{ MeV}$), and $\bar{d}$ is the average atmospheric thickness ($\sim 4 \text{ g/cm}^2$) between the detector and the Crab Nebula. The time-averaged pulsed power is then given by

$$I_{\text{AVE}} \lesssim \frac{F}{\ln(E_2/E_1)} \text{ keV cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1} \quad \text{V-4}$$

where F is given by equation V-3, and E_1 , E_2 are the lower and upper energy thresholds for LER B (725 keV and 2.3 MeV respectively). The resulting upper limit fluxes are shown in Table V-1.

The HER phase diagram shows strong evidence of a double peak occurring at the proper arrival times for pulsed emission from NP 0532. Also, the pulse shape features are in qualitative agreement with the main and interpulse peaks.

TABLE V-1
RESULTS OF PULSAR SPECTRAL MEASUREMENTS

ENERGY INTERVAL	ENERGY WINDOW THRESHOLDS	PULSED PHOTON FLUX (PHOTONS/CM ² SEC)	PULSED POWER (KEV/CM ² SEC KEV)
LER	250 KEV - 2.3 MEV	$(1.44 \pm 0.57) \times 10^{-3}$	$(6.49 \pm 2.57) \times 10^{-4}$
LER A	250 KEV - 725 KEV	$(1.20 \pm 0.52) \times 10^{-3}$	$(1.14 \pm 0.50) \times 10^{-3}$
LER B	725 KEV - 2.3 MEV	$\leq 7.85 \times 10^{-4}$	$\leq 6.79 \times 10^{-4}$
HIER	> 2.3 MEV	$\leq 8.60 \times 10^{-4}$	$I(E) \leq 1.97 \times 10^{-3}/E(\text{MEV})$ OR $\leq 2.28 \times 10^{-4}$ (FROM 2.3 - 100 MEV)
0.5 MEV	450 KEV - 550 KEV	$\leq 5.28 \times 10^{-4}$	

observed for NP 0532. However, neither peak extends 2σ or more above the average number of counts/bin. This fact is supported by the lack of a feature in the χ^2 distribution at or near the period 33.112312 ms, as seen in Figure V-7. Although the indication of a positive pulsed contribution is quite strong from the HER phase diagram, the effect is $< 2\sigma$ and cannot be strongly supported statistically. We have arbitrarily chosen the 2σ , or 95% confidence level, as the dividing line between a yes or no decision on the presence of a source contribution in this thesis. Adhering to this choice, we have quoted the HER result as an upper limit at the 2σ level.

The HER represents an integral energy interval extending above 2.3 MeV. An equation analogous to equation V-3 was used to obtain the upper limit integral pulsed photon flux above 2.3 MeV. To obtain the correction to zero g/cm^2 atmospheric depth, the attenuation coefficient for a photon energy of 8.9 MeV was assumed to hold for the entire HER. The results of this calculation are also shown in Table V-1. To obtain the average pulsed power upper limit, two methods were chosen. The necessity for methods other than that used for the LER B data can be seen from equation V-4. Since the HER is an integral channel extending, in principle, to $E = \infty$, a calculation of $\bar{I}_{AVE}$ for the HER would require the choice $E_2 = \infty$ which implies $\bar{I}_{AVE}(HER) = 0$. However, we know that the use of an average value for $I(E)$ in an unbounded energy interval is meaningless. Hence, other approaches are needed.

The first estimate assumes that the pulsed power spectrum varies as a power law in energy with a spectral index of -1.0 ($I(E)dE = kE^{-1}dE$). Knowing the upper limit pulsed photon flux we can calculate the maximum value of k from

the relation

$$F(E > E_0) = \int_{E_0}^{\infty} \frac{I(E)}{E} dE,$$

or

$$F(E > E_0) = k \int_{E_0}^{\infty} E^{-2} dE = k/E_0,$$

where $E_0 = 2.3$ MeV. From the HER upper limit photon flux we obtain $k \leq 1.97 \times 10^{-3} \text{ keV cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1}$.

The second method uses the fact that there is an efficiency rolloff for the present detector. We can therefore use an effective upper energy efficiency cutoff in equation V-4. Using the ϵ_2 curve from Figure F-3, this energy was chosen to be ~ 100 MeV. Using this choice for E_2 in equation V-4 gives

$$I_{\text{AVE}}(\text{HER}) \leq 2.28 \times 10^{-4} \text{ keV cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1}$$

from 2.3 MeV to 100 MeV. Note that these two upper limits agree at the mean energy of the interval (~ 9 MeV).

In the search for an enhancement at the 0.5 MeV annihilation line region no evidence was found from either the phase diagram or the χ^2 distribution for a measurable contribution above statistical fluctuations. 2σ upper limits were calculated using equation V-3 with a photopeak detection efficiency at 0.5 MeV = 0.786, and with $E_1 = 450$ keV and $E_2 = 550$ KeV. Note that this upper limit is consistent with the positive measurements in LER A (see Table V-1).

5.3 Discussion of Results

The present spectral measurements for NP 0532 are plotted in Figure V-8 along with previous measurements by other groups. It is immediately obvious that the present results are inconsistent with those of HILLIER et al. (1970). Our results are nearly an order of magnitude below his if his results are extrapolated to our LER region. A χ^2 statistical test of our data using a two peak model with the peak shapes the same as those in the X-ray region has shown that there is $\ll 0.01\%$ chance that the present data would allow a pulsed photon flux as high as HILLIER quotes. Note that in his results the $E^{-0.7}$ spectral shape shown in the figure was assumed, not measured, since his detector only measured an integral rate between 600 keV and ~ 9 MeV (HILLIER et al., 1970). In fact, his data would imply that the pulsed component of the total Crab Nebula emission represents the entire emission above ~ 500 keV. The present experiment measured a pulsed emission only up to 725 keV, and the results are not inconsistent with an extrapolation of the pulsed measurements at lower energies with no change in spectral index. However, we can not exclude a possible flattening of the pulsed spectrum above 725 keV from the present data. We can, however, calculate a minimum value which the spectral index can have and still be consistent with our upper limits above 725 keV. An energy flux spectrum as flat as $I(E) = 6E^{-0.5} \text{ keV/cm}^2 \text{ sec}^{-1} \text{ keV}^{-1}$ above 725 keV would be consistent with the present data. This would imply a sharp break in the pulsed spectrum, and appears highly unlikely because it would be inconsistent with the high energy upper limit measurement of SHARE et al. (1971) and a positive observation by BROWNING et al. (1971) unless

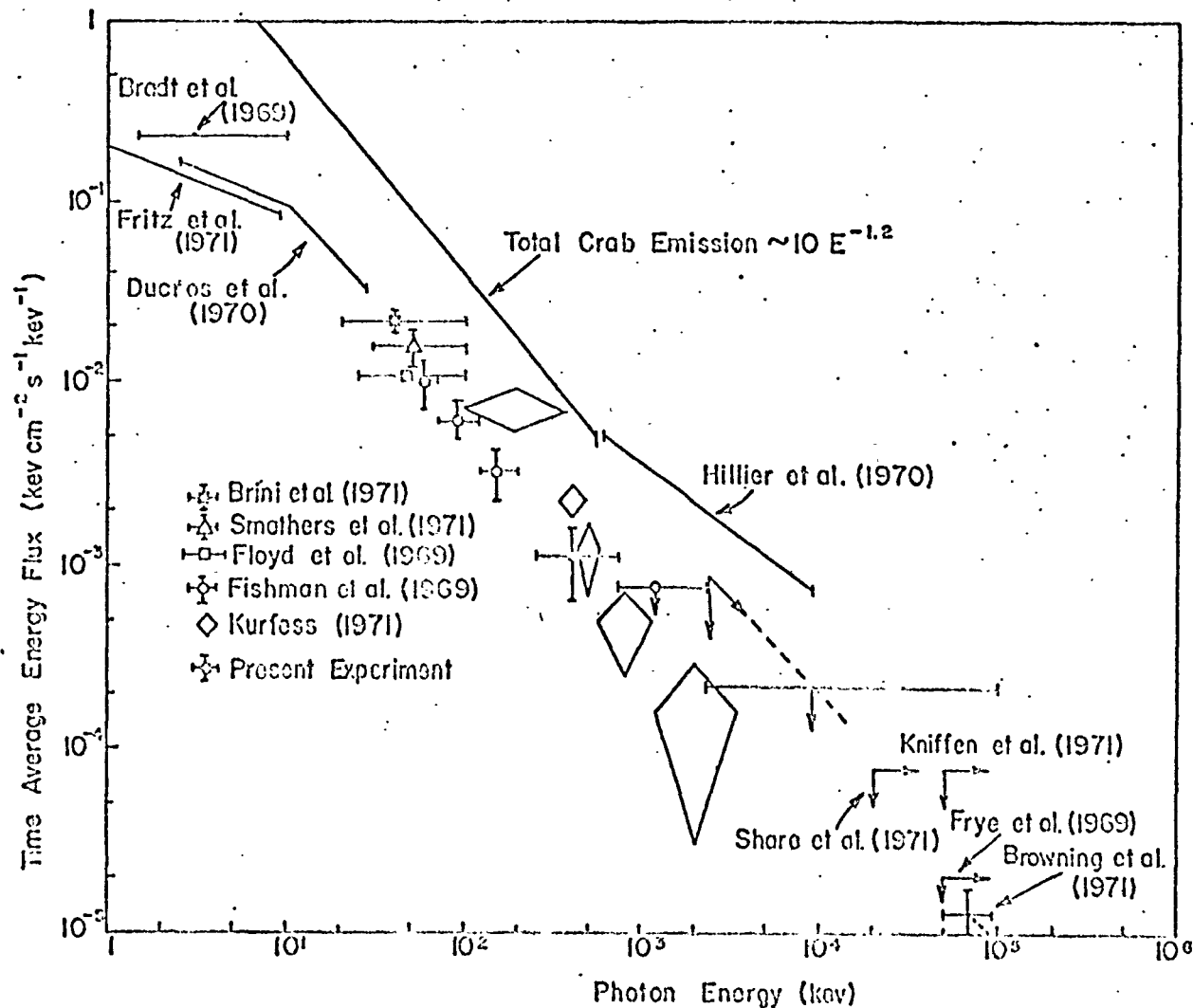


Figure V-8. Measurements of the time-average pulsed energy flux from NP 0532. The spectrum shape was assumed and not measured in results of HILLIER et al. (1970). Vertical error bars on results of present experiment represent $\pm 1\sigma$ errors due to counting statistics; the horizontal bars indicate the extent of the energy bin. Also shown for comparison is the best approximation to the spectrum of the steady Crab emission up to ~ 500 keV. (HAYNES et al; 1968; GRADER et al., 1966).

a quick steepening of the spectrum occurs. Note that the early spark chamber measurements by KINZER et al. (1970) in which a positive contribution was reported have been revised by the authors to an upper limit (SHARE et al., 1971) as indicated on the graph. This upper limit resulted from a repeat of the data analysis using a smaller angular window about the direction of the Crab Nebula. Very recent measurements of the pulsed emission of NP 0532 by VASSEUR et al. (1971) are consistent with the published results above 50 MeV. They saw a small pulsed effect, but below the 2σ level, and therefore quoted their results as an upper limit.

Above 725 keV our data is entirely consistent with the measurements of KURFESS (1971), whose experiment was nearly identical to the present one, the major difference being the fact that he has ~ 15 hrs of data viewing the Crab Nebula compared to our 4 hrs. However, the present measurement in the region from 250-725 keV (LER A) does not agree with KURFESS' results for his lowest energy bin (100-400 keV). His positive observation is higher than ours and is also higher than the results of FISHMAN et al. (1969b) in the same energy region. However, FISHMAN's results were uncorrected for detector efficiency. Note that the results of KURFESS also indicate that HILLIER's result is anomalously high.

As mentioned earlier, the interpulse to main pulse intensity ratio for the LER energy interval, 250 keV to 2.3 MeV, is 2.4 ± 1.9 . This is consistent with the trend toward a more intense interpulse peak as the photon energy increases (see Table I-1). This is larger than the value observed below 100 keV and is further evidence that the spectrum of the radiation comprising the interpulse peak is harder than that for the primary peak.

Note that above 600 keV no measurements of the steady Crab emission exist. In fact, above 100 keV the pulsed flux is more accurately measured than the total emission. In order to make a statement about the fraction of emission of the total Crab flux for our pulsed flux results, we must make an assumption about the steady Crab flux. We have assumed that the steady Crab flux continues to follow the spectrum $10 E^{-2.2}$ photon $\text{cm}^{-2} \text{sec}^{-1} \text{keV}^{-1}$ above 500 keV. On this basis our pulsed flux from 250 to 725 keV represents $15.2\% \pm 6.6\%$ of the total Crab flux. This is roughly equivalent to that observed in the hard X-ray regions below 100 keV; but disagrees with the result given by KURFESS (1971) from 100 to 400 keV. To see how the present results compare to the previous measurements, Table I-1 gives an up-to-date listing of the published information on the characteristics of NP 0532. With regard to the ratio of interpulse intensity to main pulse intensity, the present result is in agreement with the general pattern toward an increasing ratio. Also, the LER A result of 1.36 ± 1.11 is, within statistical error, in agreement with this trend. However, our results for the percentage of the total Crab radiation that is pulsed appear to disagree with the trend. The present results would predict a levelling off of the percentage pulsed flux in contradiction to the results of SMATHERS et al. (1971) and KURFESS (1971).

However, the marginal statistics in the present experiment force us to be very conservative when detailed information, other than just the existence of a pulsed component, is sought. This is evidenced by the large statistical errors attributed to the results. We can therefore not attach a great deal of significance to a result such as the percentage of the total Crab flux that is pulsed, es-

pecially since the total Crab flux used in the calculation was only estimated and does not represent a measured quantity.

The upper limit for the contribution of pulsed annihilation line radiation at 0.51 MeV is consistent with the positive pulsed flux observed in the lowest energy bin of the present experiment. This result shows that there is no strong pulsed contribution from electron-positron annihilation processes in the emitting region. This upper limit is also consistent with a similar upper limit obtained by FISHMAN et al. (1969b) for the 0.51 MeV line flux from the steady Crab.

5.4 Summary

To summarize the results of the present experiment, the following statements can be made:

(1) The Crab Nebula pulsar NP 0532 has been found to be an emitter of pulsed radiation in the energy region from 250 keV to 725 keV. Above this energy there is evidence for a pulsed effect, but not above the 95% confidence level. Our confidence that we have observed pulsed radiation with a non-directional instrument is based on

- (a) the characteristic phase plot at the expected apparent period for NP 0532,
- (b) main pulse arrival time,
- (c) main pulse - interpulse separation,
- (d) approximate pulse shapes on the two peaks, and
- (e) the indication from the χ^2 analysis.

(2) The time-averaged pulsed energy flux from 250 to 725 keV was found to be $(1.14 \pm 0.50) \times 10^{-3} \text{ keV cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1}$. Above 725 keV the upper limit calculations

gave the results shown in Table V-1.

(3) The ratio of interpulse intensity to main pulse intensity in the energy range 250 keV - 2.3 MeV was found to be 2.4 ± 1.9 . This result indicates that the radiation spectrum for the interpulse continues to be harder than that for the main pulse.

(4) The present spectral measurements of the pulsed radiation are not inconsistent with an extrapolation of the lower energy measurements with no change in spectral index. The present results do indicate that the time-averaged pulsed energy spectrum must decrease with a spectral index at least as large as -0.5 above 725 keV.

(5) Our results are clearly inconsistent with the published results of HILLIER et al. (1970). A χ^2 analysis on our LER data indicates that there is a $\ll 0.01\%$ probability that our results would include a flux as high as that given by HILLIER. The present results are consistent with most measurements at energies both below and above our energy region, except with the result of KURFESS (1971) from 100-400 keV.

The present results are not conclusive enough to make a positive statement about the spectral shape above 700 keV. Further measurements are required to clear up this question. The results do indicate that the pulsed contribution is continuing to become a larger component of the total Crab emission at these higher energies. Unfortunately, much more work must be done on both the steady and pulsed Crab emissions before the spectral shape is known with sufficient accuracy to make statements concerning what emission mechanisms are operating. No pulsed line contributions have been observed in any energy region as yet. This indicates that only continuum-producing source mechanisms are operating.

in the source region and may indicate a common process which could produce the observed emissions in all wavelength regions.

Improvements in the present measurements can be made in two ways, (1) increasing the observation time by further flights of the present detector, or (2) change the detector system in order to improve its signal-to-background ratio. Improved statistics can be obtained most efficiently by improving the signal-to-background ratio because the signal varies linearly with time whereas the noise varies as the square root of the observation time. Hence, a program of further flights with the present instrument is not the most efficient way of improving the results as the noise is decreasing only as the square root of the time.

Improvements to the present flight instrument can be made in the area of background reduction. This could be accomplished by the use of selective active shielding to achieve a gamma ray telescope type of detector and decrease the contribution to the gamma ray background from atmospheric secondaries. In addition, most of the atmospheric neutron background could be removed by using the pulse-shape discrimination (PSD) technique with the present crystal. Although neutron effects are not expected to be large in the present experiment (see Appendix D), their removal is an obvious improvement to a gamma ray experiment.

Whatever method is used to improve or extend the present measurements, it is clear that further measurements in the low energy gamma ray region are needed to obtain more definitive information on the pulsed spectrum of NP 0532. These measurements, however, should not necessarily be limited to the pulsed emission of the Crab Nebula, for any positive gamma ray measurements in the energy region from 100 keV-10 MeV could have much astrophysical significance.

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APPENDIX A

GAMMA RAY PRODUCTION MECHANISMS

1. Introduction

In Section 1.1 we noted that positive cosmic gamma ray measurements could tell us much about cosmic rays, interstellar matter, magnetic fields, and other parameters of gamma ray source regions. This is so because the astrophysical processes which produce gamma radiation depend directly on these quantities. To understand this dependence, we must consider the possible mechanisms by which gamma rays can be produced on an astrophysical scale. In this appendix I wish to discuss the major gamma ray production mechanisms, pointing out the important features of each particular mode of gamma ray production. More detailed descriptions of the processes can be found in HEITLER (1960), GINZBERG and SYROVATSKII (1964), GINZBERG (1967), ROSSI (1952), SHKLOVSKY (1960) and STECKER (1971).

2. Production Mechanisms

Basically there are two general categories of gamma ray producing interactions, 1) those processes which produce a continuum spectrum of gamma radiation, and 2) those processes which yield monoenergetic gamma rays. Neither category is more important than the other since both types are capable of yielding information about the source parameters.

We shall consider the following mechanisms, which are effective producers of photons in the gamma ray energy region.

- 1) Continuum Emission
 - a. Bremsstrahlung
 - b. Inverse Compton effect
 - c. Synchrotron radiation (magnetic bremsstrahlung)
 - d. Gamma rays produced in π^0 decay
- 2) Line Emission
 - a. Pair annihilation of e^+ and e^-
 - b. Decay of excited nuclear levels

Bremsstrahlung

Bremsstrahlung radiation is the radiation emitted by a charged particle during its deceleration in the Coulomb fields of nuclei. This radiation can be produced by cosmic rays bombarding the interstellar gas or can occur in dense source regions where high energy particles interact with the nuclei in the source region. For these inelastic interactions, in any given deflection by a nucleus, the incident particle can radiate any amount of energy up to its total kinetic energy, T . Hence all radiation frequencies are allowed up to a maximum frequency given by $\nu_m = T/h$, indicating that high energy photons can be produced in this process. The derivation of the cross sections for this process requires a quantum mechanical treatment since the process involves the interaction of the incident particle with the nuclear field and the electromagnetic field of the emitted photon.

In the case of non-relativistic electrons in the field of a nucleus of charge Z , the bremsstrahlung cross section is given by (STECKER, 1971)

$$\sigma_b(E, E_\gamma) dE_\gamma = \frac{dE_\gamma}{137} \left(\frac{e^2}{m_0 c^2} \right)^2 Z^2 \left(\frac{m_0 c^2}{E_\gamma} \right) \ln \left\{ \frac{[T^{1/2} + (T - E_\gamma)^{1/2}]^2}{E_\gamma} \right\} \frac{\text{cm}^2}{\text{nucleus}}$$

where m_0 , e , T , and E are the rest mass, charge, kinetic energy, and total energy respectively, of the electron, E_γ = the emitted photon energy, and Z = the charge of the scattering nucleus. This expression gives the differential cross section for the emission of a photon of energy between E_γ and $E_\gamma + dE_\gamma$ by an electron of kinetic energy T and total energy $E = T + m_0 c^2$.

For the scattering of heavy particles with charge ze , mass M , kinetic energy T , and total energy $E = T + Mc^2$, the expression becomes

$$\sigma_b(E, E_\gamma) dE_\gamma = \frac{1}{137} \left(\frac{z^2 e^2}{Mc^2} \right)^2 Z^2 \left(\frac{Mc^2}{E_\gamma} \right) \ln \left\{ \frac{[T^{1/2} + (T - E_\gamma)^{1/2}]^2}{E_\gamma} \right\} dE_\gamma \frac{\text{cm}^2}{\text{nucleus}}$$

Hence, the cross section varies as Z^2/M^2 where Z is the nuclear charge of the target nuclei and M is the mass of the incident particle. Due to this $1/M^2$ dependence on the incident particle mass, radiation by electrons is by far the most predominant process (the cross section for protons is nearly 4×10^6 times smaller). The Z^2 dependence shows that this process is much more likely to occur in higher Z materials and thus will most likely occur, for example, in source regions where the density of higher Z nuclei is large.

For relativistic electrons ($m_0 c^2 \ll E \ll 137 m_0 c^2 / Z^{1/3}$) the radiative cross section becomes

$$\sigma_b(E, E_\gamma) dE_\gamma = \frac{4}{137} \left(\frac{e^2}{m_0 c^2} \right)^2 Z^2 \ln \left(\frac{2E}{m_0 c^2} - \frac{1}{3} \right) \frac{dE_\gamma}{E_\gamma} \frac{\text{cm}^2}{\text{nucleus}},$$

and in the ultrarelativistic case ($E \gg 137 m_0 c^2 / Z^{1/3}$) we have

$$\sigma_b(E, E_\gamma) dE_\gamma = \frac{4}{137} \left(\frac{e^2}{m_0 c^2} \right)^2 Z^2 \ln(183 Z^{1/3} + 1/18) \frac{dE_\gamma}{E_\gamma} \frac{\text{cm}^2}{\text{nucleus}}$$

(STECKER, 1971). This equation can be written in the form

$$\sigma_b(E, E_\gamma) dE_\gamma = \frac{M}{\langle X_r \rangle} \frac{dE_\gamma}{E_\gamma}$$

where M is the mass of the target atoms (gm) and $\langle X_r \rangle$ is defined as the average radiation length (in g/cm^2) for radiative losses in the medium,

$$\langle X_r \rangle^{-1} = \frac{4}{137} \left(\frac{Z^2}{M} \right) \left(\frac{e^2}{m_0 c^2} \right)^2 \ln(183 Z^{1/3} + 1/18).$$

For interstellar matter (90% H, 10% He) $\langle X_r \rangle \cong 65 \text{ g/cm}^2$.

The intensity of bremsstrahlung photons is given by (GINZBERG, 1967)

$$I_b(E_\gamma) = \int_0^L dr \int_{E_\gamma}^{\infty} n(\vec{r}) \sigma_b(E, E_\gamma) I_e(E, \vec{r}) dE$$

photons $(\text{cm}^2 \text{ sec sr MeV})^{-1}$, where I_e is the electron intensity (electrons/ $\text{cm}^2 \text{ sec sr MeV}$), and $n(\vec{r})$ is the atomic concentration (nuclei/ cm^3) at a position $\vec{r}$ in the scattering region.

Using A-1 and assuming that $I_e(E, \vec{r})$ is independent of $\vec{r}$ we obtain

$$I_b(E_\gamma) = \frac{Mn(L)}{\langle X_r \rangle} \int_{E_\gamma}^{\infty} \frac{I_e(E) dE}{E_\gamma} \text{photons } (\text{cm}^2 \text{ sec sr MeV})^{-1},$$

where

$$n(L) = \int_0^L n(\vec{r}) dr.$$

Such bremsstrahlung radiation is generally emitted into an angular region of the order of $m_0 c^2/T$ about the direction of the electron. Hence at low electron energies the radiation can be emitted in any direction, while at relativistic and ultra-relativistic energies ($m_0 c^2/T \ll 1$) the emitted radiation is highly peaked in the direction of motion of the electron.

As equation A-2 shows, the resulting gamma ray bremsstrahlung spectrum depends strongly on the initial electron energy spectrum $I_e(E, \vec{r})$. Hence, a measurement of a bremsstrahlung spectrum gives information about the initial electron energy distribution in the scattering region. For bremsstrahlung of extragalactic origin, cosmological redshifts will modify the gamma ray spectrum. Such cosmological effects are considered in detail by STECKER (1971).

The important parameters of this electron bremsstrahlung radiation mechanism are:

(a) A continuum spectrum of gamma rays is produced, up to an energy equal to the highest electron kinetic energy, $T_{\max}$. The resulting spectral shape is strongly dependent on the initial electron energy spectrum.

(b) The bremsstrahlung cross section varies directly as the square of the charge of the scattering nucleus and inversely as the product of the emitted photon energy and the square of the incident particle mass ($\sigma \sim Z^2/M^2 E_\gamma$).

(c) For relativistic electrons the radiation is emitted within a cone of angle $m_0 c^2/T$ about the direction of the electron.

(d) A power law electron spectrum of the form $I_e \propto E^{-\Gamma}$ will produce a power law gamma ray spectrum with the same spectral index, $I_\gamma(E_\gamma) \propto E_\gamma^{-\Gamma}$.

Inverse Compton Effect

In this mechanism high energy electrons scatter with low energy photons yielding higher energy photons. The process is the inverse of the normal Compton effect which refers to the scattering of photons by electrons at rest. Viewed in the rest frame of the electron, the inverse process looks identical to Compton scattering, which is described by the Klein-Nishina formula. When transformed to the cosmic frame of reference the photon receives a portion of the electron energy. The amount of energy transferred can be large enough to create gamma ray photons ($E_\gamma > 100$ keV). In general the scattered photons have a range of energy values, even for incident electrons and photons of fixed energy. This is due to the many combinations of values which the angles of incidence and scattering can have. For an electron of energy $E = \gamma m_0 c^2$ and photon of energy ϵ , the scattered photon energy is given by

$$E_\gamma = \frac{\gamma^2 \epsilon f_1(\beta, \alpha, \alpha')}{1 + (\gamma \epsilon / m_0 c^2) f_2(\beta, \alpha, \theta')} , \quad \text{A-3}$$

where $\beta = v/c$, v = the electron velocity, $\gamma = (1 - \beta^2)^{-1/2}$, and f_1 and f_2 are dimensionless functions containing the dependence on the scattering angles α, α' , and θ' (see STECKER, 1971 for the definition of these angles).

When conditions are such that $\gamma \epsilon \ll m_0 c^2$, equation A-3 gives $E_\gamma \cong \gamma^2 \epsilon$ ($\gamma \epsilon \ll m_0 c^2$). In this case the Klein-Nishina cross section reduces to the non-relativistic Thompson cross section

$$\sigma_c \rightarrow \sigma_T = (8\pi/3) (e^2/m_0 c^2)^2 \text{ cm}^2$$

In the extreme relativistic case, $\gamma \epsilon \gg m_0 c^2$, the cross section becomes

$$\sigma_c \rightarrow \pi (e^2/m_0 c^2)^2 \left(\frac{m_0 c^2}{E} \right) [1/2 + \ln (2\epsilon/m_0 c^2)],$$

and the resulting photon energy approaches $E_\gamma \sim \gamma m_0 c^2 = E$, the initial electron energy. When $\gamma \epsilon \ll m_0 c^2$, the differential cross section for the production of a gamma ray of energy E_γ by Compton scattering is a complicated expression and is given by GINZBERG and SYROVATSKII (1964). The mean gamma ray energy is

$$\langle E_\gamma \rangle = \frac{4}{3} \gamma^2 \langle \epsilon \rangle$$

where the symbol $\langle \rangle$ denotes a mean value. This relation shows that gamma rays from 100 keV to 10 MeV can be produced by electrons in the energy range 1.4×10^8 eV to 1.4×10^9 eV when scattered off of starlight ($\langle \epsilon \rangle \sim 1$ eV).

Using these cross sections, the average time rate of energy loss that an electron of energy $E = \gamma m_0 c^2$ suffers in Compton scattering with low energy photons

$$-(dE/dt)_c = \frac{32\pi}{9} \left(\frac{e^2}{m_0 c^2} \right)^2 c \gamma^2 \rho_\gamma \text{ ergs/sec}$$

where ρ_γ is the energy density of the photon field (ergs/cm³).

The total gamma ray production spectrum is given by

$$I(E_\gamma) = \int_0^L dr \int_{E_\gamma}^\infty dE I_e(E, \vec{r}) \int_0^\infty d\epsilon n_{ph}(\epsilon, \vec{r}) (E_\gamma, E, \epsilon) \text{ photons} \\ (\text{cm}^2 \text{ sec sr MeV})^{-1},$$

where $n_{ph}(\epsilon, \vec{r})$ is the initial photon density distribution (photons/cm³ MeV) and $I_e(E, r)$ is the electron intensity dis-

tribution (electrons/cm² sec sr MeV). GINZBERG (1967) has evaluated this expression for the case of a power-law electron spectrum $I_e(E) = K e^{-\Gamma}$ electrons/cm² sec sr MeV. Using a simplified form for $\sigma(E_\gamma, E, \epsilon)$ and assuming that all scattered photons have the average photon energy $\langle E_\gamma \rangle = \frac{4}{3} \gamma^2 \langle \epsilon \rangle$, he obtains a gamma ray intensity of

$$I_c(E_\gamma) = \frac{4\pi L}{3} \left(\frac{e^2}{m_0 c^2} \right)^2 (m_0 c^2)^{1-\Gamma} \left(\frac{4}{3} \epsilon \right)^{(\Gamma-1)/2} n_{ph} K E_\gamma^{-(\Gamma+1)/2}$$

photons (cm² sec sr MeV)⁻¹,

where L is the effective pathlength for gamma ray production, and $n_{ph} = \int_0^\infty n_{ph}(\epsilon) d\epsilon$. A power law electron spectrum of index, Γ , therefore produces a power law gamma ray spectrum of index $(\Gamma+1)/2$.

The important features of this gamma ray production process are:

(a) Photons of gamma ray energies can easily be produced. The typical photon energy is $\langle E_\gamma \rangle \sim \gamma^2 \epsilon$.

(b) The mechanism yields a continuous gamma ray spectrum.

(c) The resulting gamma ray spectrum depends directly on the low energy photon number density in the source region.

(d) A power law electron spectrum produces a power law photon spectrum by the inverse Compton process.

Synchrotron Radiation

A third process which produces a continuum photon spectrum is the synchrotron mechanism (or magnetic bremsstrahlung) whereby a high energy electron radiates electromagnetic radiation in the presence of a magnetic field which has a

component in a direction perpendicular to the electron velocity. (Only electrons are considered since they are by far the strongest radiators, as will be seen). The synchrotron process is considered in great detail by SHKLOVSKII (1960) and GINZBERG (1967), and only the salient features of the mechanism are given here.

This process is the relativistic analog of cyclotron radiation by non-relativistic electrons. Recall that in cyclotron radiation the electron describes a circular (or helical) path in the field and radiates at a monochromatic frequency of $\omega_c = eH_{\perp}/m_0c$ where $H_{\perp}$ is the component of H perpendicular to the electron velocity. The charged electron radiates because it is accelerated by its movement in the magnetic field. For relativistic electrons the situation is modified. The electron (of energy E) gyrates about the magnetic field (magnitude H) at a frequency of

$$\omega_H = \frac{eH}{m_0c} \left(\frac{m_0c^2}{E} \right).$$

This result assumes that H is homogeneous and constant (that variations in H are small over one electron orbit). The total power radiated in the form of synchrotron emission by a particle of charge Z , mass M , and total energy E , is

$$P(E) = \frac{2}{3} \frac{(eZ)^4 H_{\perp}^2}{M^2 c^3} [(E/Mc^2)^2 - 1] \text{ erg/sec.}$$

We see from this equation why electrons are the most prolific radiators. Since $P(E) \sim 1/M^2$, an electron radiates $(M/m_0)^2 \sim 4 \times 10^6$ times as much power as a proton with the same E/Mc^2 ratio. An electron of energy $E = \gamma m_0 c^2$ suffers synchrotron energy losses at a rate given by

$$-(dE/dt)_{\text{sync}} = \frac{32\pi}{9} \left(\frac{e^2}{m_0 c^2} \right)^2 c \gamma^2 \rho_H$$

where $\rho_H = H^2/8\pi$ is the magnetic energy density, γ is the Lorentz factor for the electron, and c = the speed of light.

To obtain photons of gamma ray energies from this process one needs ultrarelativistic electrons ($E \gg m_0 c^2$). We therefore confine ourselves to this case. For ultrarelativistic electrons the directional radiation intensity is peaked sharply in the direction of the electron velocity vector, being emitted within a cone of angular width $\Delta\theta \sim m_0 c^2/E$. An observer will see sharp pulses of radiation of duration

$$\Delta t \sim \frac{m_0 c}{e H_{\perp}} \left(\frac{m_0 c^2}{E} \right)^2 = (mc/eH_{\perp}) (1/\gamma^2),$$

where $H_{\perp}$ is the component of H perpendicular to the electron's circular motion. When Fourier analyzed these bursts contain a nearly continuous frequency spectrum up to a critical frequency of

$$\omega_c \sim \frac{1}{\Delta t} \sim (eH_{\perp}/m_0 c) \gamma^2.$$

A rigorous solution for the emitted frequency spectrum shows that the frequency of maximum emission is $\omega_m \sim 0.29 \omega_c$. At ω_c the spectrum begins to drop off sharply. Although there is a continuum of emitted frequencies it is useful to characterize the emission as occurring at the frequency ω_c which corresponds to a photon energy of

$$E_{\gamma}(\omega_c) \sim (e\hbar H_{\perp}/m_0 c) \gamma^2.$$

This equation shows that to obtain 0.1-100 MeV photons in a 10^{-5} gauss field (interstellar space) requires electron

energies of $7 \times 10^{14} \text{ eV} < E_e < 2 \times 10^{16} \text{ eV}$. In a neutron star environment where H_1 may be 10^4 gauss at the velocity of light cylinder, we can obtain synchrotron gamma rays from 0.1-100 MeV for electron energies of $2 \times 10^{10} \text{ eV} < E < 7 \times 10^{11} \text{ eV}$. Electrons of these energies very likely will exist in rotating neutron stars (GOLD, 1969; GUNN and OSTRIKER, 1969).

Synchrotron emission is characterized by the fact that (1) the emitted radiation is largely confined to the plane containing the electron's circular motion, and (2) the emitted radiation is strongly polarized. The radiation of a single electron is generally elliptically polarized (with a very large eccentricity) in a plane perpendicular to the observer's direction (GINZBERG, 1967). For a system of electrons in a vacuum the highly beamed radiation is linearly polarized in a plane perpendicular to the direction of the observer.

If the energy spectrum of the radiating electrons is a power law

$$I_e(E) \propto E^{-\Gamma},$$

then the resulting synchrotron radiation spectrum will have the form

$$I_{\text{sync}}(E_\gamma) \propto E_\gamma^{-\alpha} \text{ photons (cm}^2 \text{ sec sr MeV)}^{-1},$$

where

$$\alpha = (\Gamma + 1)/2.$$

Note that this power law dependence is similar to that obtained for Compton radiation. Because of the large electron energies required to obtain gamma ray radiation from this mechanism, synchrotron radiation is most predominant at radio frequencies where the radiation can be produced by

lower-energy electrons ($E_e \sim 10^8 - 10^{10}$ eV).

In the above discussion we have considered the case of relativistic electrons in a vacuum to obtain the general characteristics of the synchrotron mechanism. In many cases the influence of the medium is important, especially in supernova and stellar atmospheres where dense plasmas can change the character of the radiation. Other radiation processes can occur and become significant. For example, in a plasma, electrons which are traveling faster than the phase velocity of electromagnetic waves in the plasma can radiate by the Cerenkov mechanism. In the presence of media the bremsstrahlung and inverse Compton processes can become competing production processes.

The characteristics of the synchrotron mechanism can be summarized as follows:

(a) The emitted radiation has a continuous spectrum up to an energy of the order of $E_\gamma(\omega_c) = (e\hbar H_-/m_0 c)\gamma^2$ with the maximum intensity of radiation occurring at an energy $E_{\gamma\max} \cong 0.29 E_\gamma(\omega_c)$.

(b) The radiation is highly beamed within an angle $\Delta\theta = m_0 c^2/E$ in the direction of motion of the electron (of total energy E).

(c) The emitted radiation is highly polarized (linearly polarized for a system of radiating electrons in a homogeneous magnetic field) in a plane perpendicular to the observer's direction.

(d) A unique relation exists between the electron energy spectrum and the resulting synchrotron photon spectrum. A power law electron spectrum (of index Γ) produces a power law photon intensity spectrum with spectral index $\alpha = (\Gamma+1)/2$.

(e) This mechanism is the only one where a charged particle can produce photons in a vacuum. The bremsstrahlung

and Compton processes require matter with which particles interact.

π^0 Production and Decay

The other major gamma ray production mechanism is the electromagnetic decay of neutral π -mesons ($\pi^0 \rightarrow \gamma + \gamma$) leading to a continuum spectrum of photons. This is a rather prompt decay process, having a halflife of 2×10^{-16} sec in the rest frame of the meson. The π^0 mesons are formed in a number of ways, the most important being their production in p-p interactions (since cosmic rays and the interstellar gas is predominantly hydrogen). In addition, π^0 mesons are products of the decay of various hyperons and mesons created in p-p interactions (STECKER, 1971). They can also be produced in proton-photon collisions where very high energy protons (the threshold proton energy is $\geq 10^{17}$ eV) collide with low energy photons. Another production process for π^0 mesons is proton-antiproton annihilation at rest which yields an average of four gamma rays per annihilation.

In the center of mass system of the decaying π^0 meson, the two gamma rays each have an energy ~ 70 MeV and are emitted isotropically. Due to the relativistic Doppler shift, in the cosmic frame of reference the gamma rays can have a continuum of energies extending from $1/2 E_\pi (1 - \beta_\pi)$ to $1/2 E_\pi (1 + \beta_\pi)$, where $\beta_\pi c$ and E_π are the meson velocity and total energy respectively. The photon intensity spectrum resulting from this process is peaked at an energy of $E_\gamma \approx 70$ MeV. The intensity of π^0 decay gamma rays is proportional to the proton intensity I_p , and the proton density in the interacting region ρ_p . For a power-law proton intensity spectrum $I_p(E_p) \propto E_p^{-\Gamma_p}$, the differential photon spectrum will have a broad peak around $E_\gamma = 70$ MeV, and for $E_\gamma \gg 70$ MeV will have a

power law shape of the form, $I_\gamma(E_\gamma) \propto E_\gamma^{-4/3} (r_p^{-1/2})$. Proton-antiproton annihilations at rest produce a sharper peak at 70 MeV in the differential gamma ray spectrum.

For gamma rays above 100 MeV this mechanism is expected to dominate as the source of the isotropic cosmic radiation (FAZIO, 1970). This mechanism has been considered as the source of the 100 MeV gamma ray flux from the galactic center and plane (KNIEFFEN and FICHEL, 1970). Also STECKER (1969 a,b,c; 1971) has proposed an extragalactic redshifted π^0 spectrum to explain the flattening in the assumed diffuse cosmic gamma ray spectrum observed by VETTE et al. (1970).

Electron-Positron Annihilation

A source of monoenergetic, or nearly monoenergetic gamma rays is the annihilation of positrons by electrons. Such positrons can be produced as by-products of nuclear reactions occurring in celestial source regions (whether in supernovae, stellar atmospheres, or the interstellar medium). Such positrons are formed principally in two ways. They can originate from the beta-decay positron-emitting modes of certain radionuclei produced in nuclear interactions. Examples are $p\text{-C}^{12}$, $p\text{-N}^{14}$, and $p\text{-O}^{16}$ collisions which lead to positron emitting nuclei. The second positron-producing mode is via the decay chain of positively charged mesons, $\pi^+ \rightarrow \mu^+ + \nu_\mu$ followed by $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$. This decay mode yields a wide spectrum of positron energies but of average energy much higher than that produced in beta decay processes. As STECKER (1971) points out, the positrons produced in these beta decay modes have relatively low energies and are more likely to stop and annihilate from rest to produce monochromatic 0.511 MeV gamma rays. The higher energy positrons resulting from the charged meson decay chain are more likely

to decay in flight producing a continuum photon spectrum.

The gamma ray producing electromagnetic interaction of the positron and electron can proceed in two ways, (1) the annihilation of a free positron and a free electron yielding (most frequently) two gamma rays, $e^+ + e^- \rightarrow \gamma + \gamma$, or (2) the formation of positronium and subsequent annihilation producing two or three gamma rays.

In the first case, if the annihilation occurs at rest, two monoenergetic 0.51 MeV gamma rays will result, producing a line spectrum. Note that there will be Doppler broadening of this line due to the thermal velocities of the annihilating positrons. The annihilation of relativistic positrons (of energy $E_+ = \gamma_+ m_0 c^2$) will give a continuous spectrum of gamma radiation above an energy $E_\gamma = \frac{m_0 c^2}{2}$ in the cosmic frame of reference. There is no upper bound to the possible gamma ray energies as E_γ increases without bound as $\gamma_+ \rightarrow \infty$. For ultrarelativistic positrons the resulting photons will have energies corresponding to sharp forward and backward scattering in the center of mass system, or

$$E_\gamma = (\gamma_+ + \frac{1}{2}) m_0 c^2 \quad \text{and} \quad E_\gamma = \frac{m_0 c^2}{2}, \text{ respectively.}$$

(Note that there exists a small three-photon annihilation cross section, but it is ~ 372 times smaller than the two-photon cross section, and this process is therefore usually neglected as a strong gamma ray source mechanism).

For non-relativistic positrons the total cross section for the free annihilation of positrons of energy E_+ into gamma rays is (STECKER, 1971)

$$\sigma_{an}(E_+, E_\gamma) = \pi (e^2 / m_0 c^2)^2 / \beta_+, \quad (\beta_+ \ll 1)$$

where $\beta_+ c$ is the positron velocity. For ultrarelativistic positrons ($m_0 c^2 / E_+ \ll 1$) this cross section reduces to the form

$$\sigma_{an}(E_+, E_Y) = \pi(e^2/m_0c^2) \left(\frac{m_0c^2}{E_+} \right) \left(\ln \frac{2E_+}{m_0c^2} - 1 \right)$$

where E_+ is the positron energy.

In the case of positronium formation low energy positrons and electrons combine to form a hydrogen-like system which may subsequently annihilate into gamma rays. This bound system can exist in the ground state either as a singlet ($^1S_0$) or triplet ($^3S_1$). Each system will decay in a different manner, the singlet state decaying into two gamma rays and the triplet state into three gamma rays. The decay from the triplet state occurs in 75% of the cases and produces a continuum spectrum of photons from 0 to 0.51 MeV.

The final positron annihilation gamma ray spectrum and the existence of a line contribution at 0.51 MeV from any source therefore depend upon the relative strength of beta-decay vs. pion-decay formation modes as well as the fraction of the positrons which produce positronium. As with the other production mechanisms, the final gamma ray spectrum also depends upon the above cross sections, the spectral density of positrons (cm^{-3}) and the electron density (cm^{-3}) in the source region. Note also that the 0.5 MeV line emission is not a prompt phenomenon for either mode of positron formation. In either mode the positrons must come to rest before annihilation into two 0.5 MeV photons. This means, for example, that in solar flare regions the delay time between production and annihilation for a 100 MeV positron is ~ 8 seconds (DOLAN and FAZIO, 1965). In contrast, in the interstellar medium the deceleration and annihilation of fast positrons may take $\sim 10^8$ yr (STECKER, 1970).

Decay of Excited Nuclear States

A final source of photons of gamma ray energies is the emission of gamma rays from the de-excitation of excited nuclei. Such excited nuclei are produced in nuclear reactions, mainly between protons, neutrons and the constituent nuclei of the interaction medium. Such reactions include the $p, p'\gamma$ inelastic scattering reactions of incident protons as well as other proton-induced reactions (p,n ; p,pn ; $p,2p$; p,α ; $p,2pn$) leading to prompt decay gamma rays or to beta emitters which in turn emit gamma rays and electrons and positrons at the decay rate of the emitter. The positron emitters will produce radiation as described in the previous section. Such de-excitation reactions yield prompt mono-energetic gamma rays in the energy region from 100 keV to 10 MeV. These gamma rays are characteristically different for different nuclei.

In addition, slow neutrons in the source region can combine with protons to form deuterium with the emission of characteristic 2.23 MeV formation gamma rays. For the Sun, DOLAN and FAZIO (1965), LINGENFELTER and RAMATY (1967), and CHUPP (1971), have tabulated the important proton-induced reactions which lead to prompt nuclear de-excitation gamma rays and beta-emitting nuclei.

The gamma ray production rate from nuclear de-excitation reactions depends on the number density of target nuclei and the number and spectral density of incident protons in the source region, as well as the individual interaction cross sections and the dimensions of the source region. Those target nuclei whose reaction cross sections are large or which have a large number density are likely candidates to become gamma ray producers. For solar flare emission,

proton reactions with He^4 , C^{12} , N^{14} , O^{16} and Ne^{20} should dominate. For example, the 6.13 MeV line emission from O^{16} ($p, p'\gamma$) O^{16} , the 4.43 MeV line emission from C^{12} ($p, p'\gamma$) C^{12} , and the 1.63 MeV emission from Ne^{20} ($p, p'\gamma$) Ne^{20} are expected to be strong, prompt nuclear line emissions in solar flares (CHUPP, 1971). Such nuclear transitions following the nuclear beta decay of heavier nuclei (Si^{28} , Ti^{44} , Cr^{48} , V^{48} , Ni^{56} and Co^{56}) are expected to occur in young supernovae (CLAYTON et al., 1969; CLAYTON and SILK, 1969), producing characteristic gamma ray lines. Cosmological effects may, however, cause a redshifting of the lines to lower energies giving smeared peaks. This effect, if valid, would make such line emission difficult to detect.

The 2.23 MeV neutron capture gamma ray line ($\text{H}^1 + n^1 \rightarrow \text{H}^2 + \gamma$, $E_\gamma = 2.23$ MeV) is expected to be a strong line emission process in solar flares. The neutrons are produced in a variety of nuclear reactions, primarily in proton and alpha-induced reactions with helium, carbon, and oxygen. These gamma rays are not emitted promptly in a flare due to the time of production of the neutrons and the slowing down time of the fast neutrons.

All line radiations are important because they provide direct evidence for the occurrence of specific nuclear reactions. Measurement of these line emissions can provide information about proton and neutron densities in the source region as well as charged particle reaction rates and the timescales for particle acceleration processes.

The relative importance of each of the above mechanisms for gamma ray production depends on the particle constituents and parameters of the source region, including the presence and strength of any magnetic fields. These mechanisms have been applied to many astrophysical processes

to explain observed radiation spectra (such as the diffuse cosmic gamma ray spectrum and the explanation of the galactic gamma ray emission) or to predict gamma ray production spectra in stellar atmospheres and from other celestial objects. The identification of a specific mechanism to explain measured gamma ray results is often quite difficult. In some cases only slight differences in the flux or spectral shape are expected for different production mechanisms, and the available data is not definitive enough to choose between several possible mechanisms. Nevertheless, knowledge of the specific production mechanisms operating in the source regions is the first step in the understanding of the physical processes taking place in these regions.

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APPENDIX B

A fairly complete series of pre-flight and post-flight calibrations were performed on the detector system to test its operation. The important tests, which have become nearly standard for all such gamma ray spectrometer experiments, are listed below.

1. Integral linearity tests on the electronics.
2. Differential linearity tests on the electronics.
3. Measurement of deadtime losses for the detector system.
4. Energy calibration of the NaI spectrometer on both the LER and HER ranges.
5. Photopeak angular sensitivity measurements for the NaI crystal.
6. Absolute gamma detection efficiency measurements for the NaI spectrometer.

The results of these calibration tests on the flight instrument are discussed individually below.

Integral Linearity

Integral linearity tests were made on the flight electronics using an ORTEC model 204 precision mercury relay pulser, whose linearity was $\pm 0.2\%$ of full scale. The pulser signals were fed directly into the flight preamp. Hence the entire signal handling system from preamplifier through PHA was included in the linearity measurement. The results of these measurements are shown in Figures B-1 and B-2. The maximum deviation from absolute linearity was found to be ± 0.5 channel for either the LER or HER. For a 256 channel

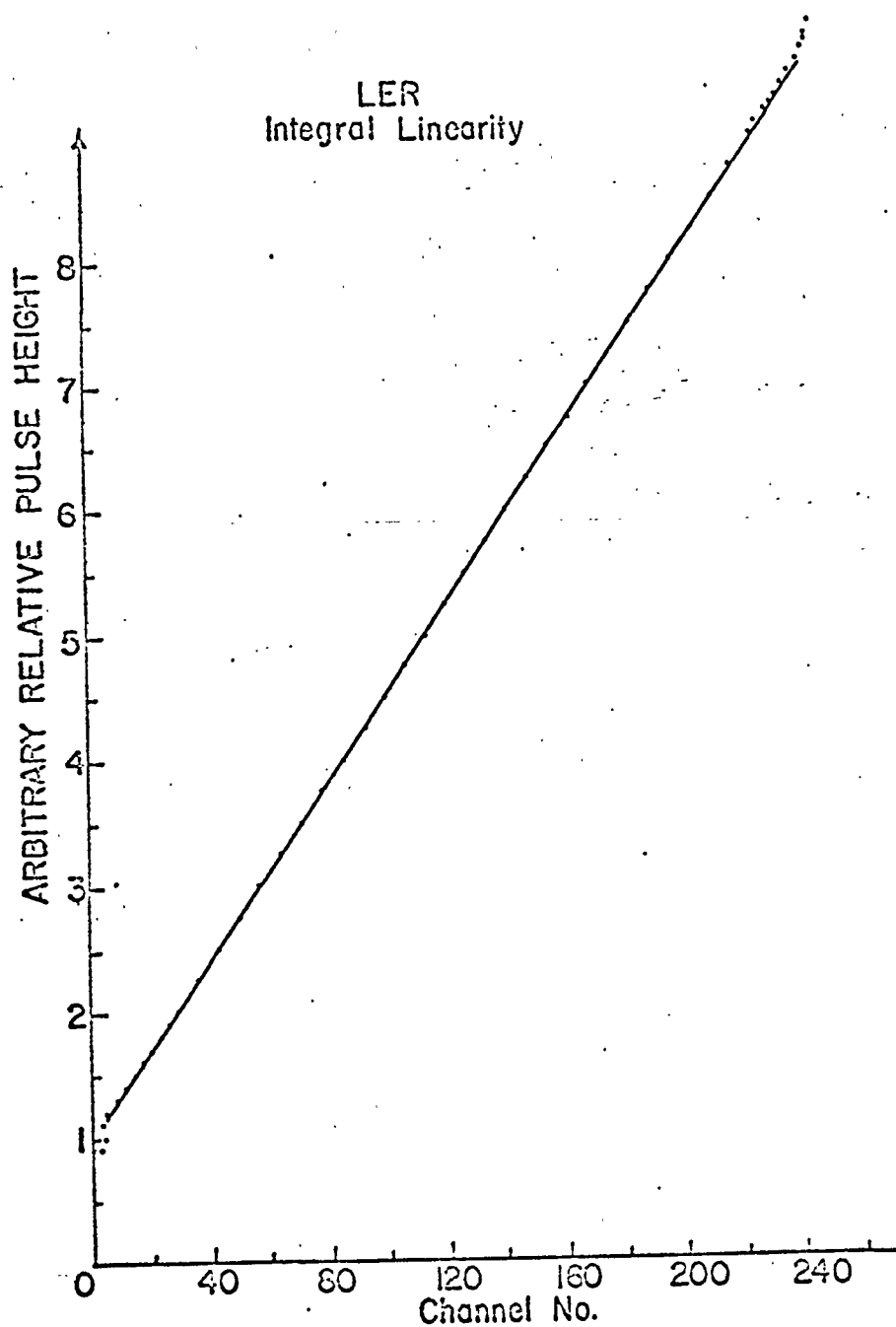
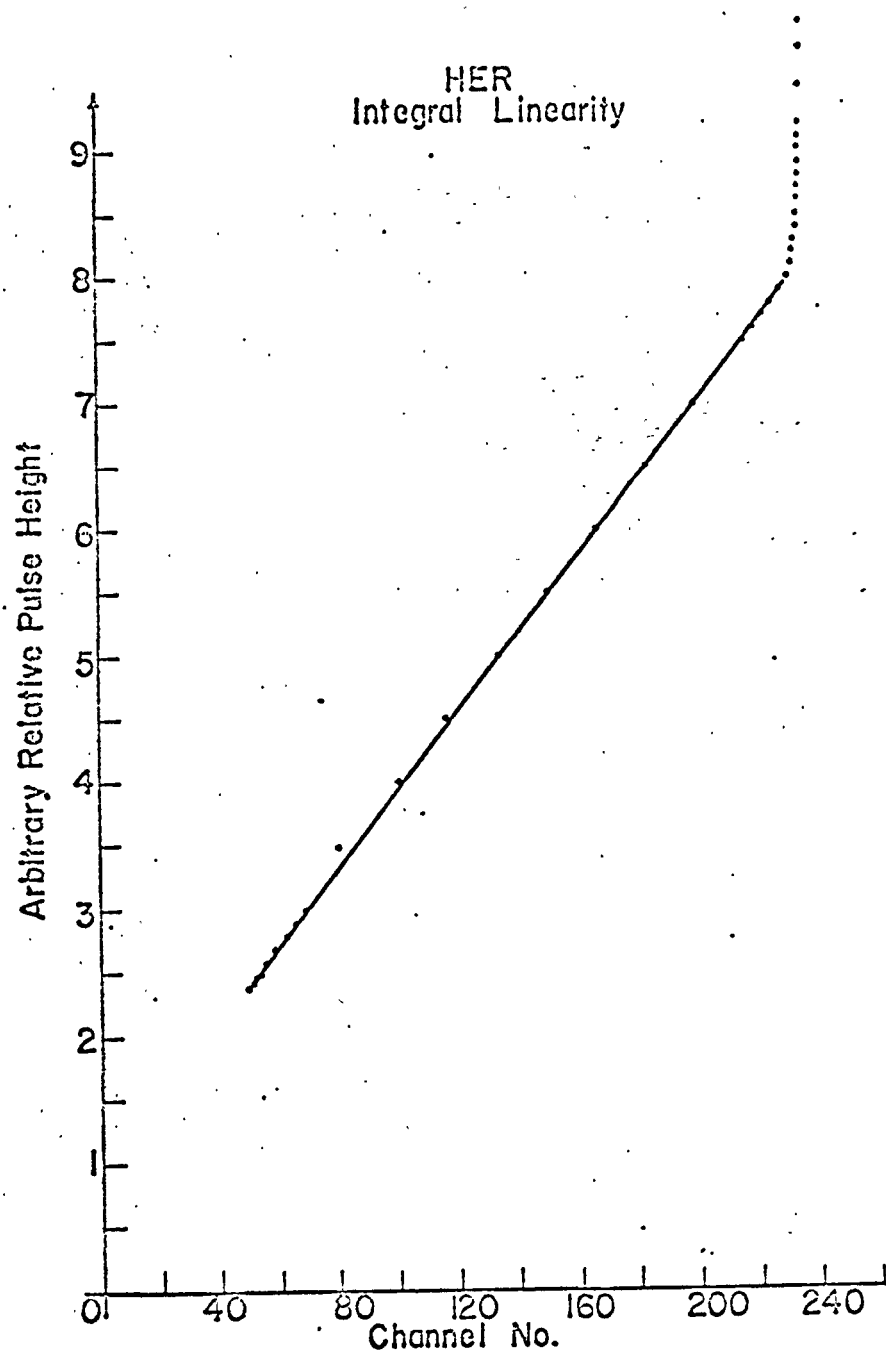


Figure B-1. Integral linearity of the flight electronics on the LER energy range.



PHA this deviation corresponds to an integral linearity of $\pm 0.5/256 = \pm 0.2\%$. This figure applies to both the LER and HER voltage ranges. It should be pointed out that both integral and differential linearity tests as performed here only check how linear the electronics is to different amplitude voltage pulses. Such tests say nothing about the linearity of the light output of the crystal for different energy gamma rays.

Differential Linearity

The differential linearity defines the uniformity of channel width across the conversion range of a pulse height analyzer. It was measured for the flight PHA by using the output of an ORTEC Model 437 time-to-amplitude converter (TAC) as an input to the PHA. Random amplitude pulses were obtained from the TAC by gating the start and stop inputs of the TAC with a random photomultiplier signal and a periodic pulse generator signal respectively. By proper choice of these gating rates random amplitude signals are generated. This is a standard method for generating random amplitude signals. For perfect linearity a pulse height analysis of these signals should yield an equal number of counts in every PHA channel. The deviation from this ideal case gives a measure of the PHA differential linearity. The differential linearity is found from the relation

$$\% \text{ DIFF LIN} = \begin{cases} + (N_{\text{max}} - N_{\text{ave}})/N_{\text{ave}} \times 100 \\ - (N_{\text{ave}} - N_{\text{min}})/N_{\text{ave}} \times 100 \end{cases},$$

where N_{min} , N_{ave} , N_{max} are the minimum, average, and maximum counts per channel respectively obtained in the channel range of interest.

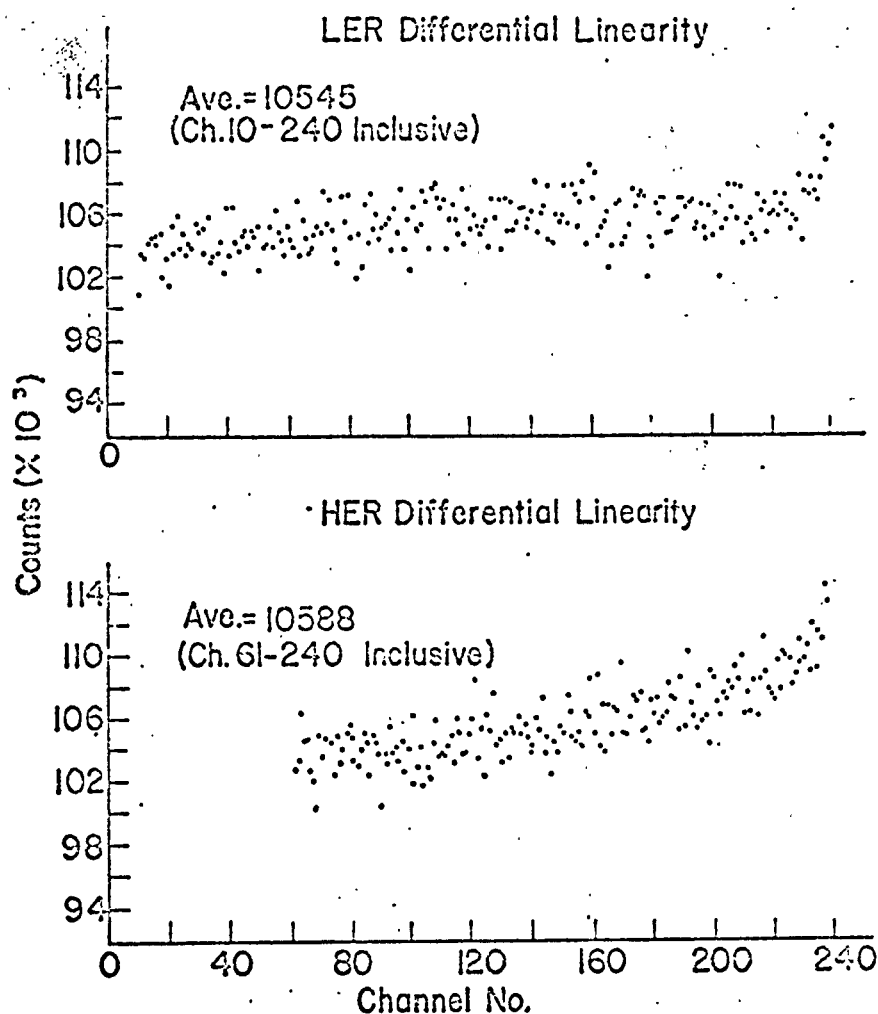


Figure B-3. (a) Differential linearity spectrum of flight pulse height analyzer on LER. (b) Differential linearity spectrum of flight pulse height analyzer on HER. See text for calculated differential linearity results for both ranges.

The results of these measurements on both the LER and HER of the flight PHA are shown in Figure B-3. On the LER, the excess in the last 10 channels is mainly due to the smearing action of the HER SELECT DISC voltage threshold. From channel 15 to 240 on the LER the maximum deviations from the average number of counts in each channel are +3.4% and -3.7%. For the HER (which starts at channel 55) smearing of the upper threshold causes a large nonlinearity above channel 240. From channels 60 to 240 on the HER the maximum deviations are +4.8% and -5.1%.

System Deadtime Losses

An accurate knowledge of the deadtime losses expected in the flight instrument is essential to minimize the errors involved in correcting the raw data. This is particularly important in a high counting rate experiment where events lost due to deadtime can be an appreciable percentage of the total number of events. Measurements of these losses were made on the flight PHA-storage buffer section, using the random input rate from the NaI spectrometer. The average input rate was varied by changing the amplifier gain and using standard radioactive gamma ray sources. Figure B-4 shows the results of the percent losses versus the average input counting rate. The percent losses are calculated from the equation

$$\% \text{ losses} = \frac{(\text{input rate}) - (\text{output rate})}{(\text{input rate})} \times 100$$

The maximum output data rate that can be achieved is 3.57 kHz. This is the data rate that would exist if the buffer were always maintained in a full condition. For comparison, on the same graph is shown the losses which would be obtained if

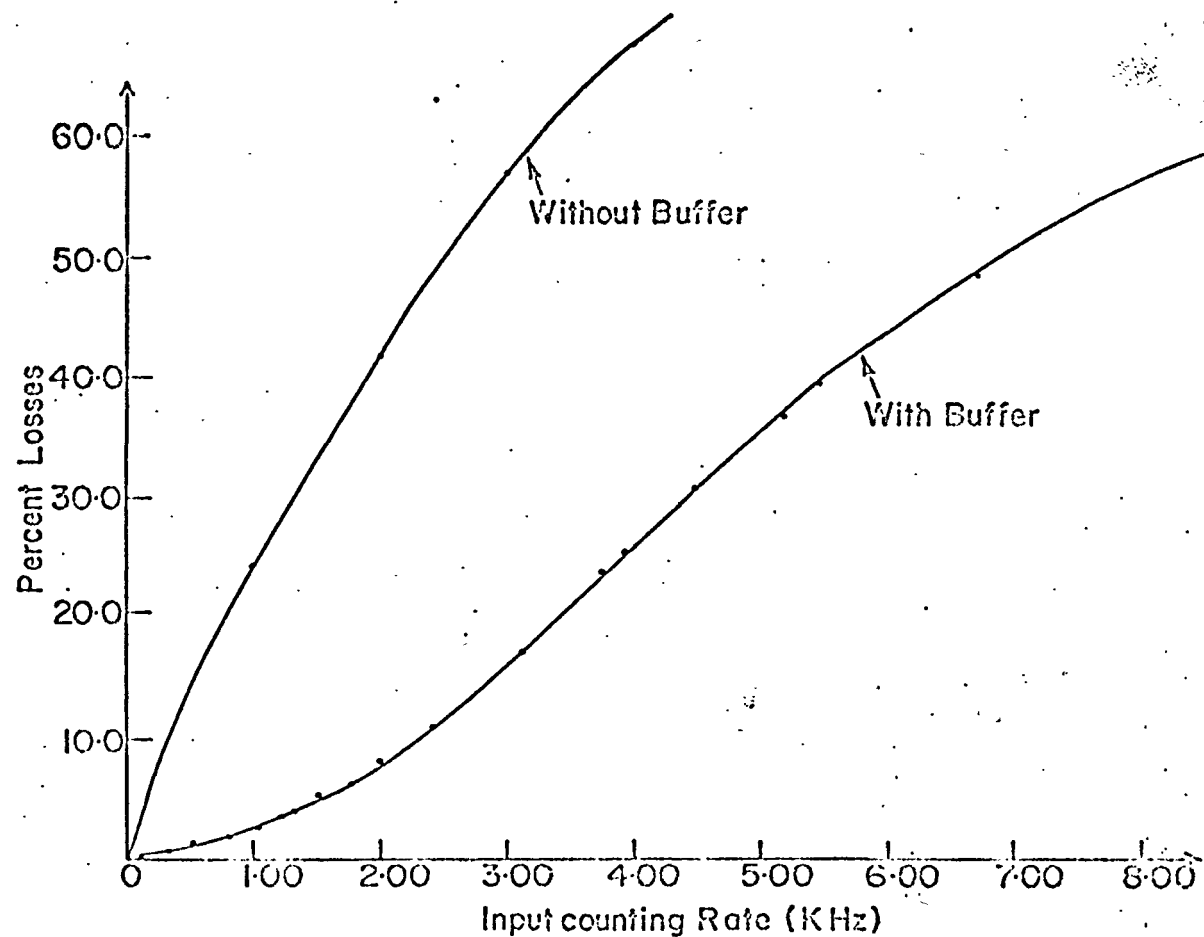


Figure B-4. Percent deadtime losses versus input counting rate for flight storage buffer. Also shown is a curve of the losses expected for a bufferless system. This deadtime curve is used to correct the data.

no buffer were used; i.e., if the random input data were transmitted to ground at a periodic rate of 3.57 kHz without buffer storage. As is seen, considerable improvement in deadtime losses is achieved through use of the buffer.

The calibration curve of Figure B-4 was used to correct the flight data for deadtime effects.

Gamma Ray Peak Position Linearity

One of the most important calibrations for a gamma ray spectrometer is the gamma ray peak position energy calibration of the detector. Assuming that the electronics has perfect integral linearity, this calibration measures the linearity of the light output versus photon energy curve for the NaI(Tl) crystal. Such light output has been observed to be non-linear for NaI(Tl) crystals by HEATH (1964). The effect is roughly 10% at 2.6 MeV for a 3" x 3" crystal such that the light output is ~10% lower than expected from a linear extrapolation from lower energies. The calibrations were made with the gain stabilization section in operation to correct for any gain shifts in the electronics. The results of this calibration for the LER and HER ranges are shown in Figures B-5 and B-6. The figures include the radioactive sources and peak energies used in the measurements. Note that these energy calibrations are valid for the post gain shift part of balloon flight 558P (the entire time at float altitude; see Section 3.3 for a discussion of this gain shift). For this energy calibration the lower Co^{60} peak (1.17 MeV) was forced to remain in channel 113. These curves indicate that the LER extends from 250 keV to 2.3 MeV and the HER from 2.3 MeV to 7.5 MeV, with the last 20 channels of the HER giving an integral counting rate above 7.5 MeV. The energy

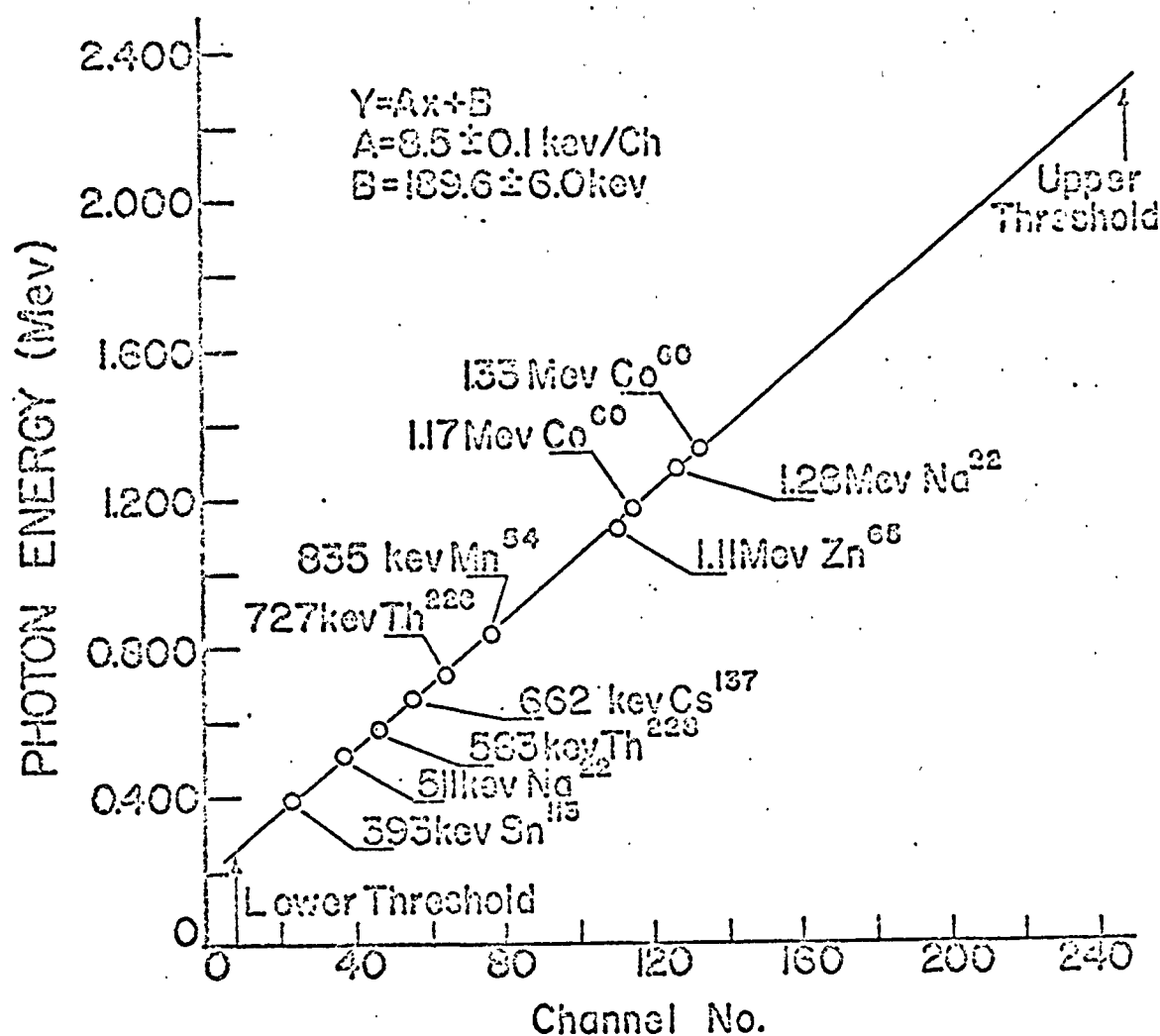


Figure B-5. Gamma ray peak position linearity for LER. The solid line represents a computer least squares linear fit to the data, giving the indicated slope and intercept values. Note that this curve is the post gain shift calibration.

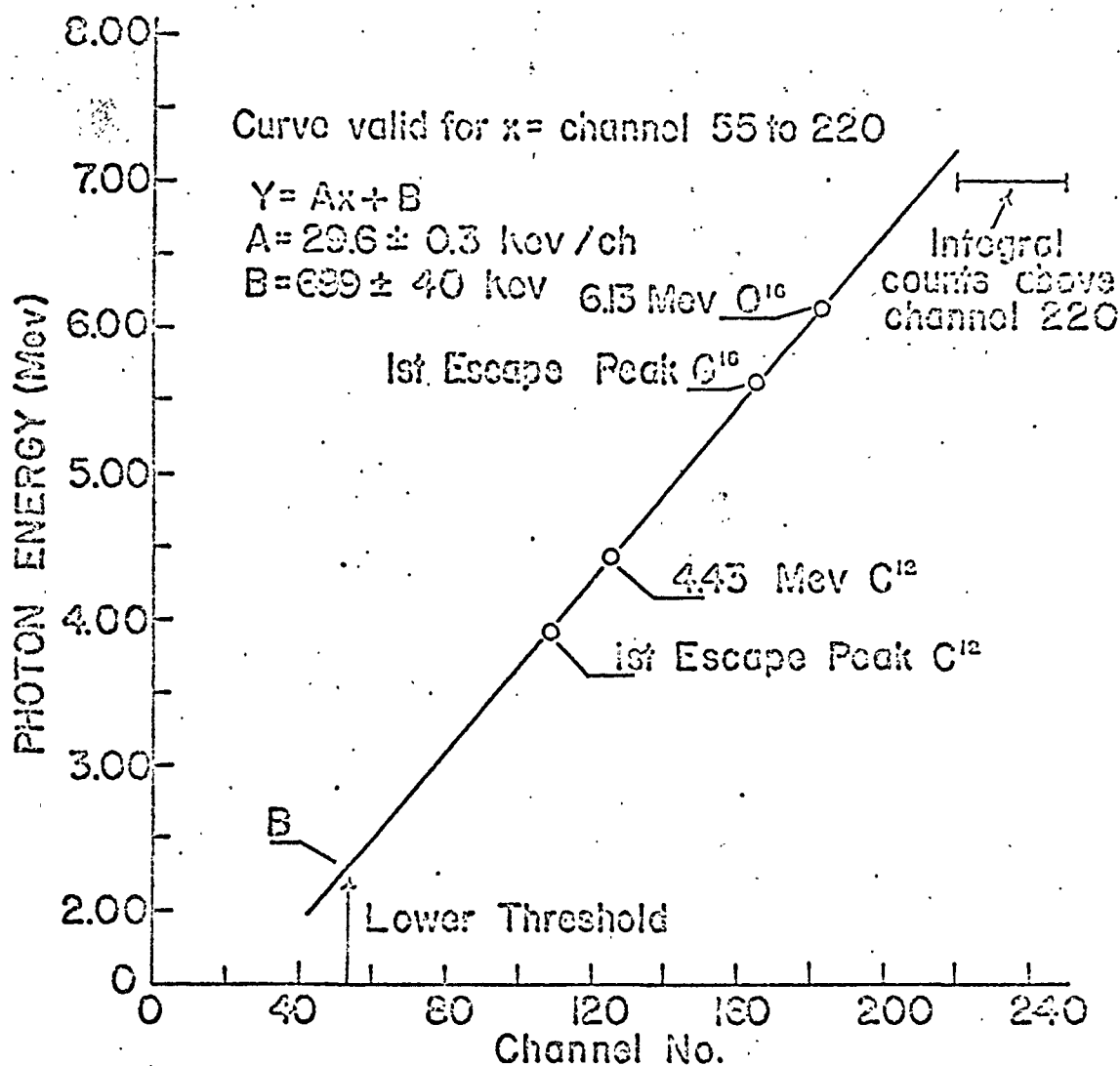


Figure B-6. Gamma ray peak position linearity for HER. The solid line represents a computer least squares linear fit to the data, giving the indicated slope and intercept values valid from channel 55 to 220. Note that this curve is the post gain shift calibration.

calibrations of Figures B-5 and B-6 are valid for the data presented in this thesis.

Relative Photopeak Directional Sensitivity

One of the reasons for choosing the present detector was the fact that it has an anisotropic directional sensitivity to radiation impinging from different directions. Detector sensitivity is defined as the response of a detector, in counts per unit time, for a unit flux of incident radiation (number/cm² sec). In general the sensitivity S_i is a function of the direction of incidence of the radiation and its energy, and is normally the product of the detector's efficiency and area. Thus, $S(E, \theta, \phi) = A(\theta, \phi) \times \epsilon(E, \theta, \phi)$, where E is the energy of the incident radiation, θ and ϕ specify the direction of the radiation, and $A(\theta, \phi)$ is the projected area and $\epsilon(E, \theta, \phi)$ the interaction efficiency for radiation in this direction.

To measure this sensitivity, careful laboratory measurements were made with monoenergetic gamma ray sources. The source was placed far enough from the detector to simulate parallel radiation. A (source + background) - (background) accumulation was made at various angles between the source and the detector symmetry axis. Ratios of the number of counts in the photopeak region in a given direction θ , to the counts obtained at $\theta=0^\circ$ were then calculated. A plot of these ratios versus θ gives a map of the relative photopeak directional sensitivity of the detector. The results of these measurements for two sources (Cs^{137} , $E_\gamma = 0.662$ MeV, and Th^{228} , $E_\gamma = 2.62$ MeV) are shown in Figure B-7. For each curve, the relative sensitivity is normalized to 1 at $\theta = 0^\circ$. At 0.662 MeV the sensitivity is quite peaked in the forward direction

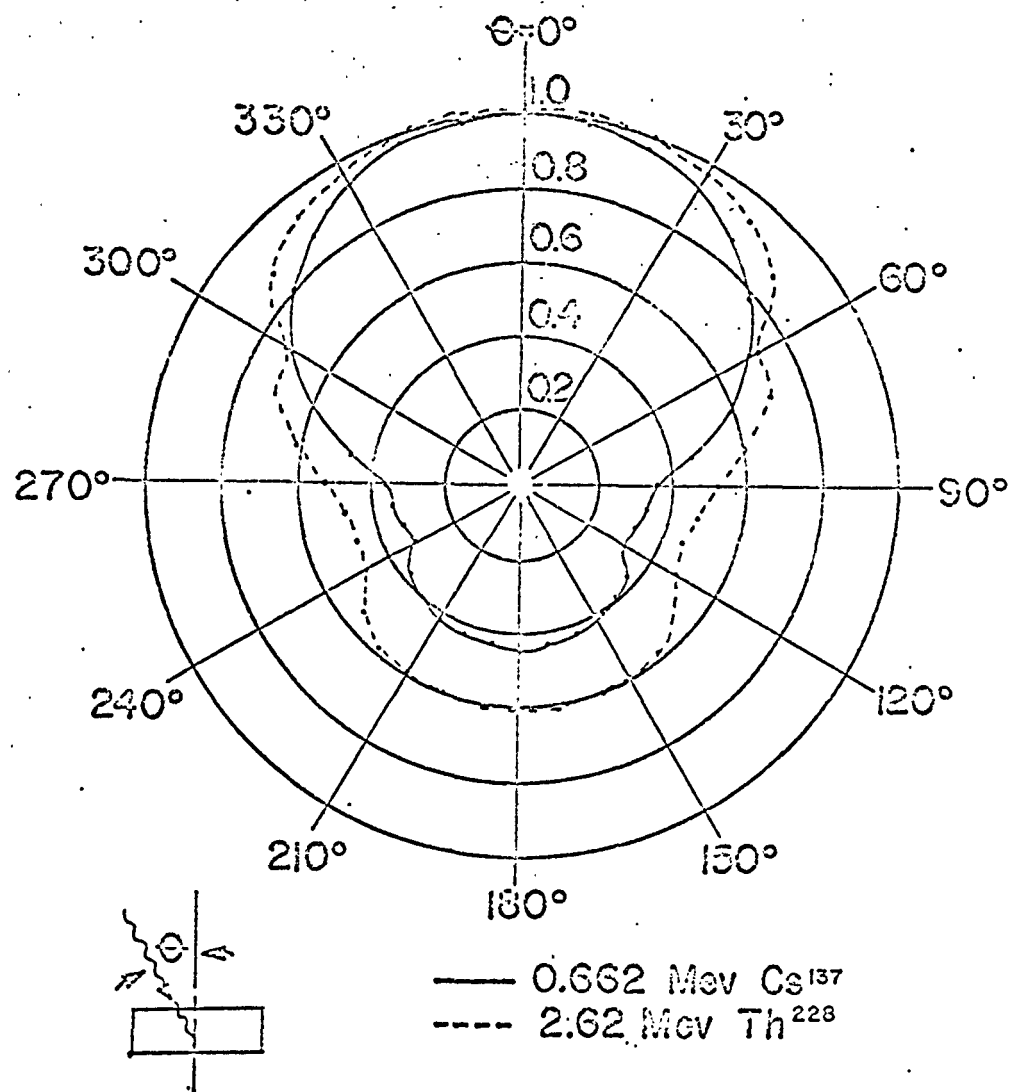


Figure B-7. Photopeak angular response of flight spectrometer at 662 keV and 2.62 MeV. The angle θ is measured with respect to the crystal symmetry axis.

($\theta = 0^\circ$), having a front-to-side ratio of $R(\theta = 0^\circ/\theta = 90^\circ) = 2.8/1$ and a front-to-back ratio of $R(\theta = 0^\circ/\theta = 180^\circ) = 2.3/1$. Even at 2.62 MeV the response is quite anisotropic. The reduction in sensitivity for angles between 120° and 240° is due to attenuation in the thick aluminum mounting plate, phototubes, and bases. The detector was assumed to have isotropic response with respect to the azimuthal angle since the crystal is azimuthally symmetric.

These curves indicate that the present detector has directional properties even though it is flown as an omnidirectional instrument (it is not actively or passively shielded in any directions to reduce background counting rates).

Gamma Ray Detection Efficiency

Laboratory measurements of the variation of absolute detector efficiency versus photon energy were not made for the present detector. Instead, the efficiencies for the present instrument were obtained by interpolation of the Monte Carlo calculations of MILLER, REYNOLDS, and SNOW (1958) for the size of the present crystal. The shape of the response to monoenergetic radiation was obtained from the energy response measurements on large crystals by KOCKUM and STARFELT (1959). To verify the accuracy of the calculated efficiencies for the present spectrometer, absolute photopeak efficiency measurements were made with the present crystal at two energies using calibrated gamma ray sources (source intensity known to $\pm 5\%$). The comparison of these measured results and the calculations of MILLER, REYNOLDS, and SNOW is shown in Table B-1. The agreement is certainly close enough to justify using the Monte Carlo results in the present analysis.

TABLE B-1

COMPARISON OF
CALCULATED AND MEASURED PHOTOPEAK EFFICIENCIES

Photon Energy (MeV)	Measured Photopeak Eff.	Calculated Photopeak Eff. (Miller, Reynolds, Snow)
0.662	0.70 ± 0.04	0.738 ± 0.008
1.114	0.49 ± 0.02	0.560 ± 0.007

The detector efficiencies required in the pulsar analysis are calculated in Appendix C along with a complete discussion of the energy response of the detector. The reader is referred to this appendix for further information on the absolute detector efficiency and energy response.

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APPENDIX C

DETECTOR EFFICIENCY AND ENERGY RESPONSE

1. Introduction

In this appendix calculations of the detection efficiency and energy response of the present gamma ray spectrometer are given. The results of these calculations are used in Section V of the thesis to convert the measured pulsar counting rates into pulsed photon fluxes.

The problem of converting a measured pulse height spectrum into a primary photon spectrum is a difficult one for gamma ray measurements in the energy region from ~ 200 keV to ~ 20 MeV in inorganic crystals. This is so because three processes contribute significantly to the electromagnetic interaction cross section in this region, 1) the photoelectric process, 2) the Compton process, and 3) the pair production process. The dominant interaction mode is the Compton effect, with the photoelectric process beginning to dominate at the low energy end of the interval and pair production becoming dominant at the higher energies (see Figure II-1).

The difficulty in converting from a measured energy loss spectrum to an input photon spectrum arises because there is not always a one-to-one correspondence between incident photon energy and the energy loss deposited in the scintillation crystal. Each of the three interaction processes yields secondary electrons whose energies, T_e , are related in different ways to the initial photon energy, E_γ .

The basic relationships between T_e and E_γ for the three processes are (BIRKS, 1964).

$$\text{Compton: } T_{ec} \text{ varies from 0 to } T_{ec \text{ max}} = E_\gamma / (1 + m_0 c^2 / 2E_\gamma)$$

$$\text{Photoelectric: } T_{ep} = E_\gamma - B_e$$

$$\text{Pair Production: } T_{epp} = E_\gamma - 2m_0 c^2$$

where m_0 is the electron rest mass and B_e is the binding energy of the atomic electron ejected in the photoelectric process.

The situation is even more complicated than this because in larger crystals multiple processes often occur for a single photon event. For example, a pair production event produces two 0.51 MeV positron annihilation gamma rays, one or both of which could then interact in the crystal via the Compton process giving a total energy loss between T_{epp} and E_γ . Or the secondary photon resulting from a Compton interaction of a gamma ray could in turn interact by the Compton or photoelectric process. These multiple processes can result in the total absorption of the initial photon energy and therefore help to increase the relative area in the full energy peak region. An energy loss spectrum for incident monoenergetic gamma rays shows contributions for almost any energy loss $\lesssim E_\gamma$, since the multiple interaction events (combined with the detector energy resolution smearing) fill in the regions not allowed by the single interaction events. As is readily seen, the unfolding of a pulse height spectrum can be quite a task, especially when the input gamma ray spectrum is not smooth, but contains line

features.

Stated mathematically, we see that a gamma ray spectrum $N(k)$ yields a pulse height distribution $P(\epsilon)$ in a spectrometer, where k denotes photon energy and ϵ the pulse height. The two distributions are related by

$$P(\epsilon)d\epsilon = d\epsilon \int_0^{k_{\max}} N(k) K(k, \epsilon) (1 - e^{-\mu L}) dk, \quad C-1$$

where $K(k, \epsilon)$ is the response function of the spectrometer for monoenergetic gamma rays, $k_{\max}$ is the maximum photon energy in the gamma ray spectrum, μ is the total attenuation coefficient (cm^2/g) of the crystal at the energy k , and L is an effective crystal length (g/cm^2). Knowing $P(\epsilon)$, the problem of obtaining $N(k)$ reduces to the determination of $K(k, \epsilon)$ with sufficient detail and accuracy. The usual solution to the unfolding problem (see for example KOCKUM and STARFELT (1959), BERGER and DOGGETT (1956), or KOCH and WYCKOFF (1958)) is to treat this equation as a matrix equation,

$$\langle P(\epsilon) \rangle = M \langle N(k) \rangle \quad C-2$$

where $\langle P(\epsilon) \rangle$ and $\langle N(k) \rangle$ are one-column matrices and M is an $n \times m$ matrix called the response matrix. Each of its elements gives the sensitivity of the spectrometer for a pulse height bin $\Delta\epsilon_i$ at ϵ_i to a unit gamma ray flux in the energy interval Δk_j at k_j . The elements of this matrix are experimentally determined for a given spectrometer by measuring the response to a number of standard monoenergetic gamma ray calibration sources. $\langle N(k) \rangle$ is then obtained from equation C-2 by multiplication of $\langle P(\epsilon) \rangle$ by the inverse matrix, M^{-1} .

In the present case we do not wish to perform a

complete unfolding process. The two questions which we must answer are:

1. What is the average weighted detection efficiency effective for each of the energy intervals chosen in the pulsar analysis, and
2. What percentage of the counts observed in a given energy bin are due to incoming photons of energy above the energy bin.

Since these questions have to be answered for only four pulse height bins (LER, LER A, LER B, and HER), it is not necessary to calculate a complete response matrix. However, the same techniques are used to answer these questions as are required to construct such a response function, in that knowledge of the spectrometer response $K(k, \epsilon)$ is required. The present calculations are only a small sample of the more general problem of generating a complete response matrix for the detector. We need to know what average weighted detection efficiency is needed in equation V-1 to convert the measured counts to a photon flux and what is the magnitude of the contribution of higher energy photons to a given pulse height interval. To answer these questions we must know how the probability of a photon giving a pulse height between the upper and lower thresholds of the i th interval (ϵ_{iu} and ϵ_{il} respectively) varies with photon energy. In calculating this probability we must know the detector response function in sufficient detail.

Mathematically we need the quantity

$$P_i(k) = \int_{\epsilon_{il}}^{\epsilon_{iu}} K(k, \epsilon) (1 - e^{-\mu l}) d\epsilon \quad C-3$$

as a function of photon energy, k . The determination of the average weighted efficiency for the i th pulse height interval

is then obtained from the expression

$$\bar{P}_i = \frac{\int_{\epsilon_{il}}^{\epsilon_{iu}} P_i(k) N(k) dk}{\int_{\epsilon_{il}}^{\epsilon_{iu}} N(k) dk}. \quad C-4$$

The fractional contribution of higher energy photons to the i th pulse height interval is given by the equation

$$R_i = \frac{\int_{\epsilon_{iu}}^{\infty} P_i(k) N(k) dk}{\bar{P}_i \int_{\epsilon_{il}}^{\epsilon_{iu}} N(k) dk}. \quad C-5$$

In general, no smooth functional relationship can be written down for $P_i(k)$ for use in the integral equations, C-4 and C-5. To obtain an approximate solution, the integrals were numerically integrated. Equations C-4 and C-5 become, under this approximation,

$$\bar{P}_i = \sum_{\substack{j=1 \\ (\epsilon_{il})}}^{n(\epsilon_{iu})} P_i(k_j, \Delta k_j) \int_{k_j - \frac{\Delta k_j}{2}}^{k_j + \frac{\Delta k_j}{2}} N(k) dk \bigg/ \int_{\epsilon_{il}}^{\epsilon_{iu}} N(k) dk, \quad C-6$$

and

$$R_i = \sum_{\substack{j=1 \\ (\epsilon_{iu})}} P_i(k_j, \Delta k_j) \int_{k_j - \frac{\Delta k_j}{2}}^{k_j + \frac{\Delta k_j}{2}} N(k) dk \bigg/ \bar{P}_i \int_{\epsilon_{il}}^{\epsilon_{iu}} N(k) dk. \quad C-7$$

2. Detector Response and Calculation of $P_i(k)$

The response function $K(k, \epsilon)$ for the flight spectrometer was constructed as follows. The fully corrected experimental response spectra of KOCKUM and STARFELT (1959) were used to

approximate the shape of the response of the present 11 1/2" diameter x 4" thick NaI detector to parallel monoenergetic gamma radiation. Their results (KOCKUM and STARFELT, 1959) which I have used were obtained with a 5" diameter x 4" thick NaI(Tl) crystal spectrometer. They used a Pb source collimator of 4.5 cm diameter and a source to crystal distance of 75 cm, and obtained fully corrected response curves for six monoenergetic gamma ray sources at 1.28, 4.43, 6.13, 11.7, 17.6, and 20.3 MeV (KOCKUM and STARFELT, p. 176). Since the only information used from their results is the shape of the response curve, it was felt that their results for the 5.4 cm diameter collimator used with a 5" diameter crystal represented a good approximation to parallel radiation incident on our larger 11 1/2" diameter crystal.

Since the pulsar energy spectrum is not expected to contain a complex line structure, a rough determination of $K(k, \epsilon)$ will suffice in the present calculations. A comparison of the collimated and uncollimated results for the single crystal spectrometer in KOCKUM and STARFELT shows that only minor differences in response shape occur, and these differences are negligible for the present case. To check on how well their curves represent the response shapes for the present detector, response curves at 1.1 MeV (Zn^{65}) and 6.13 MeV were measured with the present detector for comparison with their results. The 6.13 MeV line was obtained from the reaction $\text{C}^{13}(\alpha, n)\text{O}^{16}$ in a curium-carbon source (DICKENS and BAYBARZ, 1970). Figure C-1 shows the results of these measurements compared to the curves of KOCKUM and STARFELT made at 1.28 MeV and 6.13 MeV. Only minor differences appear, and the use of their response shapes seems entirely reasonable.

To obtain a normalization for the curves, the area under each response curve was made equal to the total interaction efficiency, $1 - e^{-\mu L}$, at that energy. The values of the

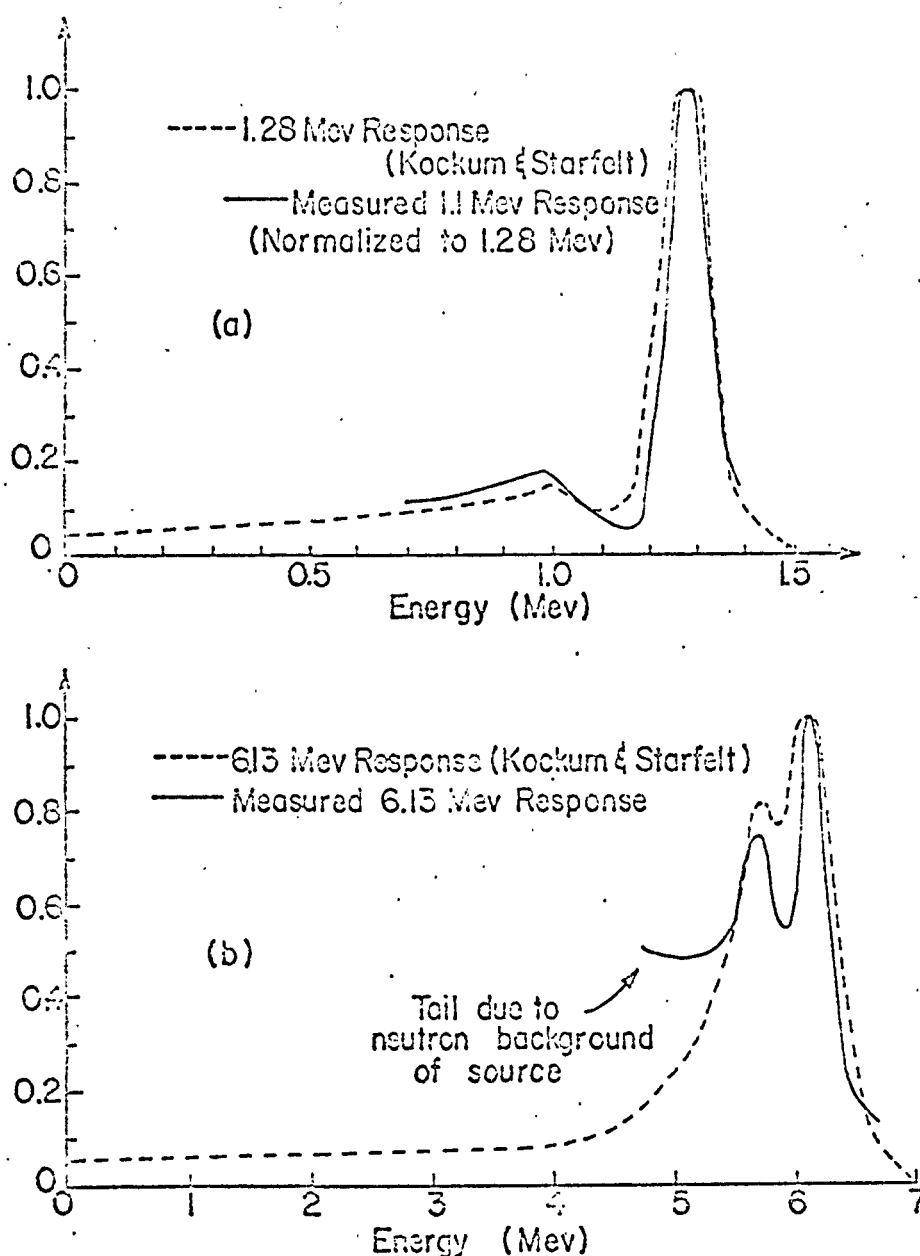


Figure C-1. Comparison of response shape measurements of KOCKUM and STARFELT (1959) to measurements for present spectrometer at two photon energies. For each set of curves the photopeak amplitudes have been arbitrarily normalized to 1.0. The measured 1.1 MeV response curve was expanded to place the photopeak at 1.28 MeV. The tail in the measured 6.13 MeV response is due to neutrons, to a continuum spectrum produced by fission products of ^{244}Cm , and to gamma ray lines from the decay of several isotopes (DICKENS and BAYBARZ, 1970). These effects were not corrected for; hence the curve is truncated after the 1st escape peak of the 6.13 MeV gamma ray line.

interaction efficiencies for various energies were obtained by interpolation of the Monte Carlo calculations of MILLER, REYNOLDS, and SNOW (1957 and 1958) for the size of the present spectrometer. In the region between 200 keV and 1.28 MeV where no response curves existed, curves were generated using an interpolation of the photofractions for NaI crystals for a broad parallel beam of radiation as calculated by MILLER, REYNOLDS, and SNOW (1958) and STEYN and ANDREWS (1969). The photopeak and Compton components were approximated with rectangular shapes.

In the region 1.28 - 4.43 MeV, response curves were obtained at energies of 1.8 MeV (Bi^{207}) and 2.62 MeV (Th^{228}) by direct measurement with the 11 1/2" diameter flight spectrometer using standard sources placed far enough away from the crystal to simulate parallel radiation. The major features (photopeak, Compton continuum, and 1st and 2nd escape peaks) of the resulting spectra were then qualitatively fit by rectangular shapes. (The results of this procedure for the 2.62 MeV response curve are shown in Figure C-2).

As done previously, the area under each response curve was set equal to the total interaction efficiency at that energy. The interaction efficiencies at these energies were obtained by interpolation of the MILLER, REYNOLDS, and SNOW data as well as from calculations using the absorption coefficients for NaI found in EVANS (1955). This procedure assured that the curves were normalized with respect to one another.

The resulting discrete set of response curves used for the present detector are shown in Figure C-2. At photon energies where a response curve did not exist, an interpolation procedure was used to obtain the response. This interpolation is quite acceptable since very little difference in shape or interaction efficiency occurs between successive response

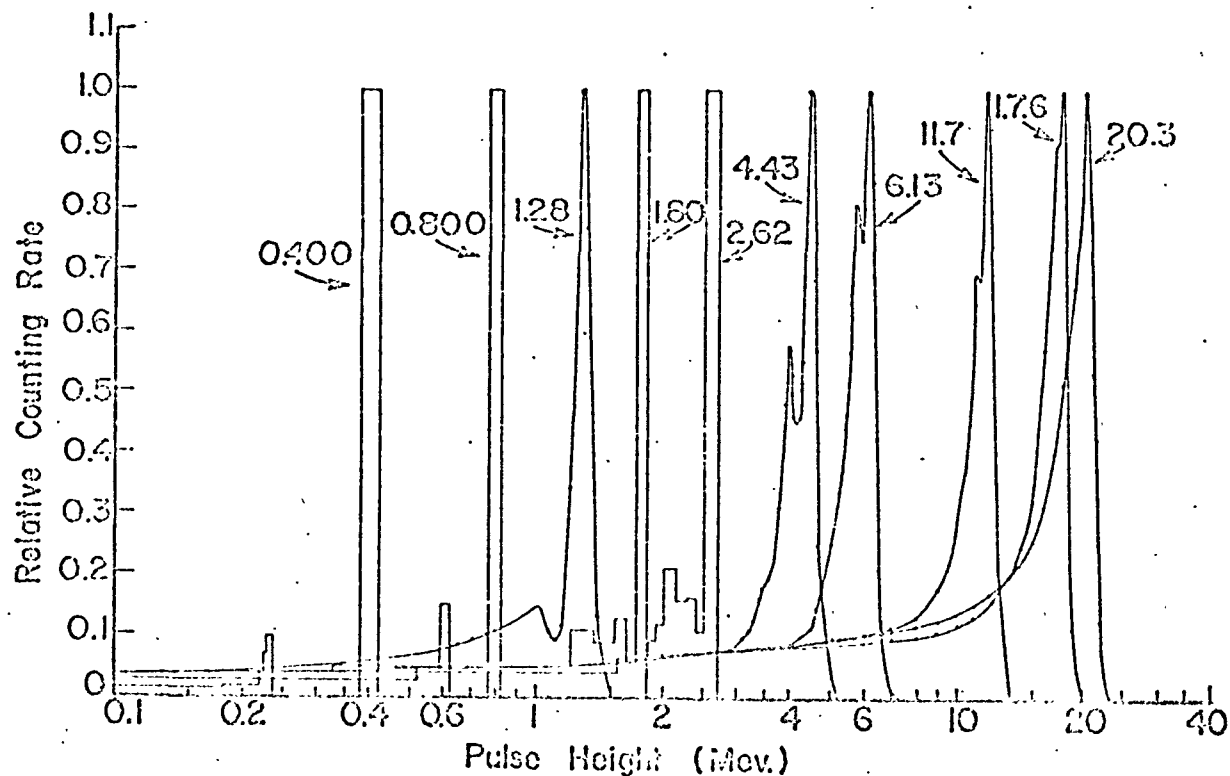


Figure C-2. The complete set of response curves for parallel incidence of monoenergetic radiation for the present spectrometer. All curves are arbitrarily normalized to a full energy peak amplitude of 1.0. Each curve represents the response to photons of the indicated energies (MeV).

curves.

Given this set of response spectra and using the interpolation method, the determination of the probability $P_i(k)$ for the pulse height intervals $i = 1$ (LER), 2 (LER A), 3 (LER B), 4 (HER) reduces to calculating the ratio of the area under each curve from $k = \epsilon_{il}$ to ϵ_{iu} to the total area under each curve; i.e.,

$$P_i(k=E_o) = \frac{\text{(Area under } k=E_o \text{ response curve from } \epsilon_{il} \text{ to } \epsilon_{iu})}{\text{(Total area under } k=E_o \text{ response curve)}}$$

This calculation was done graphically and was repeated for each response curve for a given pulse height bin. The whole procedure was then repeated for each of the pulsar energy bins. The results of these calculations are shown in Figures C-3 and C-4 for the four intervals, LER, LER A, LER B, and HER. As is expected, as long as the photon energy, k , is between ϵ_{il} and ϵ_{iu} , the probability decreases slightly due to the decrease in interaction efficiency with energy. When $k > \epsilon_{iu}$ the large photopeak area no longer falls within the pulse height window and the probability falls rapidly. The bending over of the ϵ_1 and ϵ_2 curves for HER interval at higher photon energies is due to self-gating losses caused by the charged particle shield and is discussed later.

3. Calculation of $\bar{P}_i$ and R_i

The curves of P_i generated above were used to provide the values of $P_i(k_j, \Delta k_j)$ in equations C-6 and C-7 to determine $\bar{P}_i$ and R_i for each interval. The remaining quantity needed to evaluate equations C-6 and C-7 is a value for $N(k)dk$, the differential pulsed photon spectrum (photons/cm²secMeV).

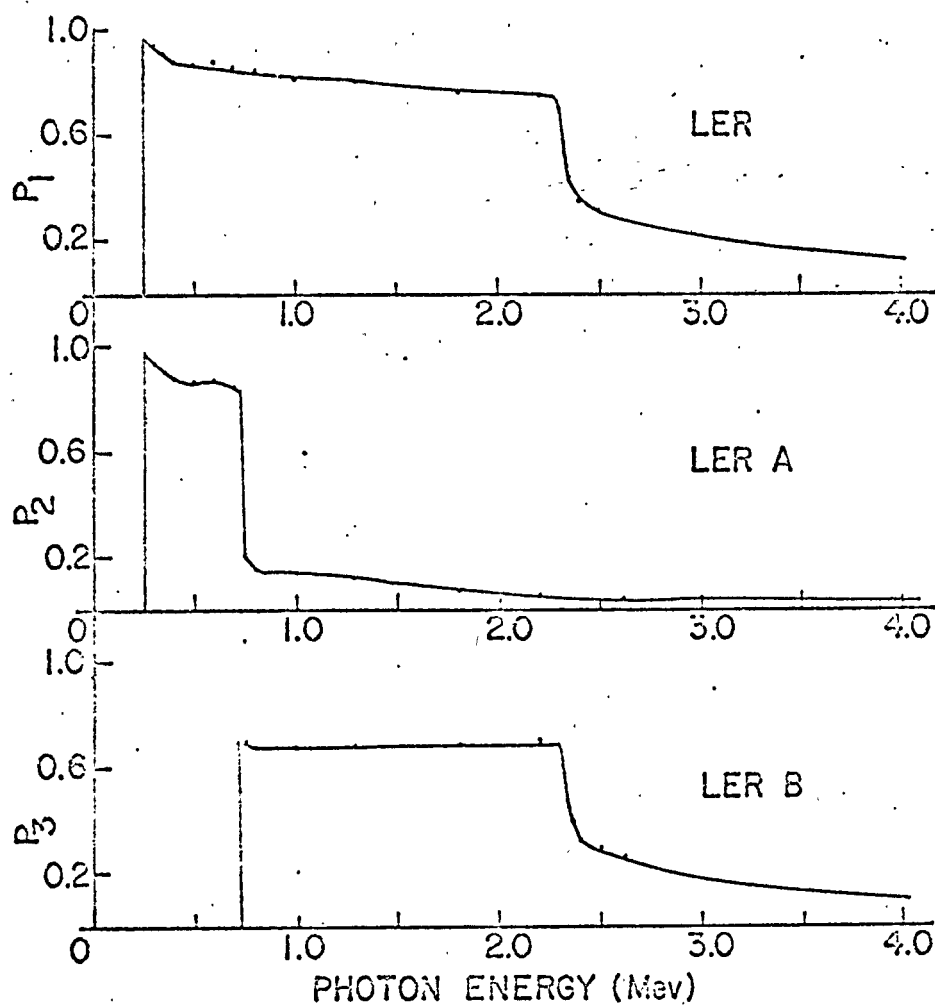


Figure C-3. Calculated detection efficiencies, P_i , for LER (P_1), LER A (P_2), and LER B (P_3) as a function of photon energy.

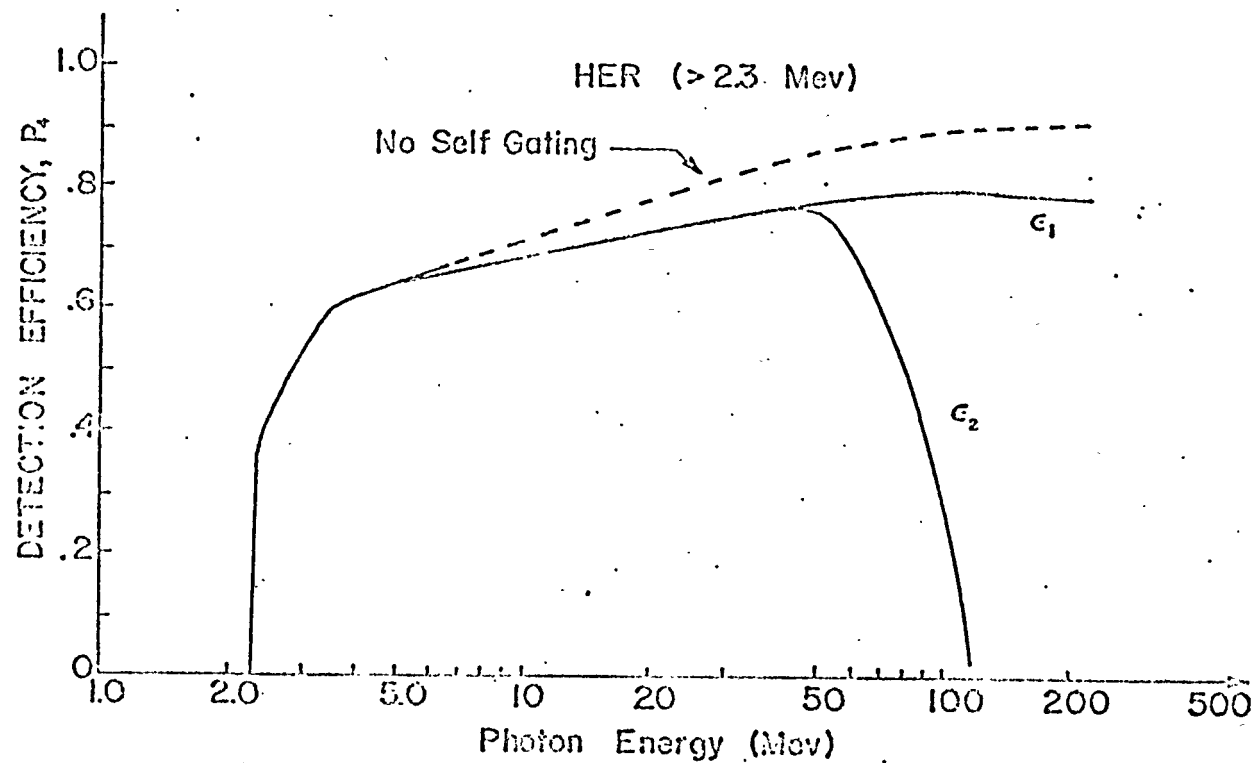


Figure C-4. Calculated detection efficiency for HER (P_4). The dashed curve is the total interaction efficiency $\epsilon = 1 - \exp(-\mu L)$. Curves ϵ_1 and ϵ_2 , which include self-gating effects, are calculated from equations C-11 and C-12 respectively.

Since this is the quantity we are trying to determine from this experiment, we do not know its value. As a first estimate of its form we can assume that, within the errors of this calculation, an extrapolation from lower energy pulsar measurements is valid. FISHMAN et al. (1969) have found that a power law of the form $N(k)dk \sim Ck^{-2.2}dk$ photons $\text{cm}^{-2}\text{sec}^{-1}\text{MeV}^{-1}$ best approximates their measurements of the pulsed energy spectrum of NP 0532 in the region 45 - 200 keV. The author has therefore chosen the functional form. $N(k) \propto k^{-2}dk$ for use in the present calculations. The -2.0 spectral index was chosen over -2.2 mainly for ease of calculation. The difference resulting from this choice is completely negligible compared to the final $\pm 20\%$ error assigned to the results of this appendix. The results of the evaluation of equations C-6 and C-7 using the indicated approximations are shown in Table C-1 below.

TABLE C-1

CALCULATED DETECTION EFFICIENCIES ($\bar{P}_i$) AND
PERCENT CONTRIBUTION OF HIGH ENERGY PHOTONS (R_i)

<u>i</u>	<u>Energy Interval</u>	<u>Pulse Height Interval</u>	<u>$\bar{P}_i$</u>	<u>R_i</u>
1	LER	250 keV-2.3 MeV	0.871 $\pm$ 20%	0.02 $\pm$ 20%
2	LER A	250-725 keV	0.90 $\pm$ 20%	0.06 $\pm$ 20%
3	LER B	725 keV-2.3 MeV	0.68 $\pm$ 20%	0.05 $\pm$ 20%
4	HER	>2.3 MeV	—	—
5	0.5 MeV	450 keV-550keV	0.786 (Photopeak efficiency)	—

The first important point to note from these results is that the $P_i(k)$ vs. k curves are quite flat for $\epsilon_{il} < k < \epsilon_{iu}$ and fall off rather sharply as k becomes larger than the upper window energy. This flatness of the efficiency curve lends support to the assumption that we can, with little error, use a weighted average detector efficiency $\bar{P}_i$ valid over a rather large energy interval in converting measured counts to a pulsed photon flux. The low R_i values show that there is little error involved in assuming that the large majority of the measured counts in a given energy bin result from photons whose energies lie solely within the boundaries of the bin. This is a consequence of the high photopeak efficiency of the present spectrometer coupled with a pulsed photon spectrum which is falling rather steeply.

The values of $\bar{P}_i$ and R_i in Table C-1 were used in the pulsed photon flux calculations presented in Section V of the thesis.

4. High Energy Self Gating Effects

The large 11 1/2" diameter x 4" thick NaI(Tl) detector makes a good "total absorption" spectrometer. This is because the relatively high Z of 53 for I (Na has a Z of 11), the high density of 3.67 g/cm³, and the large crystal size permit a complete containment of all of the energy of a photon event up to reasonably high gamma ray energies. However, at higher gamma ray energies the detection efficiency will begin to decrease due to self gating effects in the detector. It is this effect which we now consider.

In NaI gamma rays of energy > 10 MeV interact predominantly by the pair production process (EVANS, 1955). As the gamma ray energy increases, it becomes very likely in

the high Z NaI crystal that the initial pair production interaction will initiate an electromagnetic cascade shower as a result of the bremsstrahlung energy losses of the resulting electron-positron pair. The initial electron pair soon cascades into a large shower of lower energy secondary photons and electrons. It is this partitioning of the initial photon energy among many lower energy secondary photons and electrons which enables the crystal to contain a high energy event. As the gamma ray energies increase, however, more and more events occur in which the total energy cannot be contained within the crystal. If the energy lost from the crystal in the form of electrons or photons is sufficient to exceed the energy threshold of one of the plastic charged particle shield cups, the event will be vetoed as a neutral event. These losses are called self-gating losses and they become important for determining the detector efficiency at higher photon energies.

KANTZ and HOFSTADTER (1954) point out that most of the energy carried away from the crystal in shower interactions will be by gamma rays whose energies lie near the minimum of the absorption cross section versus energy curve (which for NaI would be gamma rays from 1 to 5 MeV). Gamma rays of these energies have only a small probability of interaction in the 1 cm thick charged particle shield, but if there is a sufficient number of these photons, the probability of at least one interaction can become appreciable. Also, in the higher energy events there are electrons with sufficient energy and long enough range to cause self-gating effects. This results from the fact that in pair production interactions, all modes of division of the photon energy between the two electrons are nearly equally probable (ROSSI and GREISEN, 1941), and hence high energy electrons do result

a large fraction of the time.

KANTZ and HOFSTADTER (1953 and 1954) have done considerable work on the containment of energy from electron-induced electromagnetic shower events in large blocks of various materials. They investigated the energy deposition from shower interactions in various parts of an absorber using a monoenergetic incident electron beam from an accelerator. Their results apply to a collimated beam incident at the center of one face of the absorber and thus represent an idealized situation. The use of their results for the present detector is therefore only an approximation, since for interactions occurring close to the edge of the NaI crystal, edge effects will modify the results considerably and will tend to increase the self-gating effects.

An incident high energy gamma ray requires roughly one interaction length before producing an electron pair. Thus it appears that a larger crystal is required to contain the same energy for a photon-induced shower. However, the energy of each pair electron is less than the initial photon energy. Each pair electron is more easily contained than a single electron of energy equal to the initial gamma ray energy. We shall assume here that the energy containment results of KANTZ and HOFSTADTER (1954) for electron-induced showers will hold for equal energy photon-induced showers.

For NaI the critical energy (that energy at which radiation energy losses equal ionization energy losses for electrons) is $E_c = 17.4$ MeV (BERGER and SELTZER, 1964) and the radiation length is $X_0 = 2.52$ cm, as calculated from equations in ROSSI (1952). The present spectrometer is therefore 11.6 radiation lengths in diameter and 4.05 radiation lengths thick. From the results of KANTZ and HOFSTADTER we estimate the following percentage containment of energy

loss in the present detector for incident photons of the indicated energies.

<u>Photon Energy (MeV)</u>	<u>% Energy Contained</u>
26	100%
60	95
90	75
119	70
141	60
185	55

These results are to be regarded as only a rough approximation of the average results expected for shower events in NaI since the cascade shower interaction process is highly variable for these energies. However, the results do indicate that up to ~ 100 MeV the present crystal is a fairly good total absorption spectrometer.

To make an estimate of the self-gating losses for the present crystal I have used two methods. As a first estimate of the effect, I have performed an evaluation identical to that of FORREST (1969) which is based on the simplified cascade shower theory of WILSON (1951 and 1952). The problem is to find the probability that a high energy gamma ray event will produce a self-gating interaction in the CPS cups. We assume (as does FORREST) that only the initial pair-produced electrons contribute to self-gating process. This neglects any photons which escape from the crystal. WILSON (1951) states that the number of electrons (not secondaries) at a distance t from the place of pair production is

$$n(t) = 2 \exp(-t/R_{\pi}) ,$$

where R_{π} = pair range (the average distance traveled by pair-produced electrons). This pair range is given by

$$R_{\pi} = \ln 2 [(1+1/W) \ln(W+1) - 1] - R_{ms}$$

In this equation R_{π} is in radiation lengths, W is the initial photon energy (in shower energy units, i.e. multiples of $E_c \ln 2$) and the R_{ms} term contains the correction due to multiple scattering ($\lesssim 0.06$ radiation length for photon energies $> E_c$). If the pair producing interaction occurs at the depth $t = 0$, the probability that one or more electrons appears at a depth t is

$$P(t) = n(t) / \int_0^{\infty} n(t) dt = \frac{1}{R_{\pi}} \exp(-t/R_{\pi}). \quad C-8$$

The probability that an incident gamma ray will produce a pair in dt at a depth t is just

$$P_1(t) dt = \frac{dt}{R_{pp}} \exp(-t/R_{pp}), \quad C-9$$

where R_{pp} = interaction length for pair production. Once the pair is produced at the depth t , equation C-8 can be used to express the probability that at least one electron will penetrate the remainder of the crystal, a distance $L-t$, and escape. This probability is given by

$$P_2(t) = \frac{1}{R_{\pi}} \exp[-(L-t)/R_{\pi}].$$

Conversely the probability that no electrons will escape is given by

$$P_3(t) = 1 - P_2(t) = 1 - \frac{1}{R_{\pi}} \exp[-(L-t)/R_{\pi}]. \quad C-10$$

Note that the use of L = crystal thickness here is a good approximation only for gamma rays incident on the flat face of the detector. In general the effective crystal thickness for the present detector varies greatly with angle of incidence. Since we want to know the detector response to parallel radiation on the symmetry axis, the use of the value L for the effective detector thickness is reasonable here.

This result basically assumes that the shower does not spread laterally to a great degree, or that the pair electrons move roughly in the same direction as the initial photon.

Combining equations C-8 and C-10 we obtain for the efficiency for a gamma ray to interact in the detector and not produce self-gating the relation

$$\epsilon_1 = \int_0^L \frac{1}{R_{pp}} \exp(-t/R_{pp}) \left\{ 1 - \frac{1}{R_{\pi}} \exp[-(L-t)/R_{\pi}] \right\} dt,$$

or

$$\epsilon_1 = \frac{1}{R_{pp}} [1 - \exp(-L/R_{pp})] - \frac{R_{pp}}{R_{\pi} - R_{pp}} [\exp(-L/R_{\pi}) - \exp(-L/R_{pp})].$$

C-11

This relationship was used in the HER efficiency calculations and the results are seen in Figure C-4. The curve labelled ϵ_1 is the efficiency including this self-gating, while the dashed line is the detection efficiency if no self-gating correction is applied, $\epsilon = 1 - e^{-\mu L}$.

As a second estimate of the self-gating effect I have used the following model. The KANTZ and HOFSTADTER results above indicate that at a given photon energy, on the average, a certain percentage of the total energy is not contained within the crystal. I have assumed that the escaping energy is divided equally among photons whose energy lies at the minimum of the absorption cross section versus energy

energy curve for NaI. This energy was taken to be 2 MeV. For example at $E = 90$ MeV roughly 25% of the energy, or ~ 23 MeV, is assumed to escape in the form of ~ 11 photons, each of energy 2 MeV. The probability that at least one such photon will interact in the 1 cm thick charged particle shield is

$$P_4(E_\gamma) = \sum_{i=1}^{n(E_\gamma)} 1 - \exp(-\mu_2 d),$$

where d = thickness of CPS (~ 1 g/cm²), and μ_2 = interaction mean free path for a 2 MeV gamma ray in plastic (cm²/g), and $n(E_\gamma)$ = the number of escaping 2 MeV photons. Using this equation the estimate of the detection efficiency including these self-gating effects becomes

$$\epsilon_2 = \{1 - \exp[-\mu(E_\gamma)L]\} P_4(E_\gamma) \quad \text{C-12}$$

for $E > E_c$.

$n(E_\gamma)$ is determined from the percent energy containment results of KANTZ and HOFSTADTER as listed earlier. Once again these results represent a highly idealized case, but do give an indication of the effect of the escaping energy in the form of photons. The results for this estimate of self-gating effects are shown in Figure C-4 as the ϵ_2 curve.

The results of the first method represent a very small correction to the curve which includes no self-gating. This is due to the fact that even though the initial pair electrons may be of high energy, their range is short due to radiation and ionization losses. Hence they can be contained within the crystal. Recall of course that this method does not consider the production of the secondary photons and

electrons and their possible escape and detection in the charged particle shield.

Under the assumptions of the second method the self-gating losses become quite large as energy increases and reach a point where every event is vetoed by the charged particle shield. This qualitative result is more what is expected to occur, since for a large amount of energy escaping from the crystal there will on the average be a large number of escaping secondary particles or photons of sufficient energy to be detected in the charged particle shield. Although the second estimate is idealized, it probably more closely represents the true self-gating losses.

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APPENDIX D

ATMOSPHERIC GAMMA RAY AND NEUTRON BACKGROUNDS

1. Gamma Ray Background Contributions

The ability of any balloon-borne gamma ray detector to measure very low fluxes from the Sun or other extraterrestrial sources is severely restricted by the high intensity of background radiation present in the atmosphere. This is particularly true in the case of an isotropic (or omnidirectional) detector which has approximately equal sensitivity to radiations impinging from different directions. It is the purpose of this appendix to discuss the continuous and line contributions to the background counting rates which are due to atmospheric gamma rays and neutrons.

The atmospheric gamma ray flux at balloon altitudes has been measured for energies in the range 0.1 - 10 MeV by PETERSON et al. (unpublished measurements) and above 30 MeV by FICHTEL et al. (1969). Both measurements were made at an atmospheric depth of 3.5 g/cm^2 at a geomagnetic latitude of $\lambda = 40^\circ\text{N}$. Figure D-1 shows PETERSON'S measured spectrum above 100 keV, which is a relatively smooth continuum except for the annihilation line contribution at 0.5 MeV. Note that the measurements of PETERSON do not represent a true photon flux ($\text{photons cm}^{-2}\text{sec}^{-1}\text{MeV}^{-1}$) but rather an energy loss spectrum in their detector ($\text{counts cm}^{-2}\text{sec}^{-1}\text{MeV}^{-1}$). The results of FICHTEL et al., also shown in Figure D-1, have been corrected for efficiency and therefore represent a photon flux. Below 500 keV the results of PETERSON et al. should

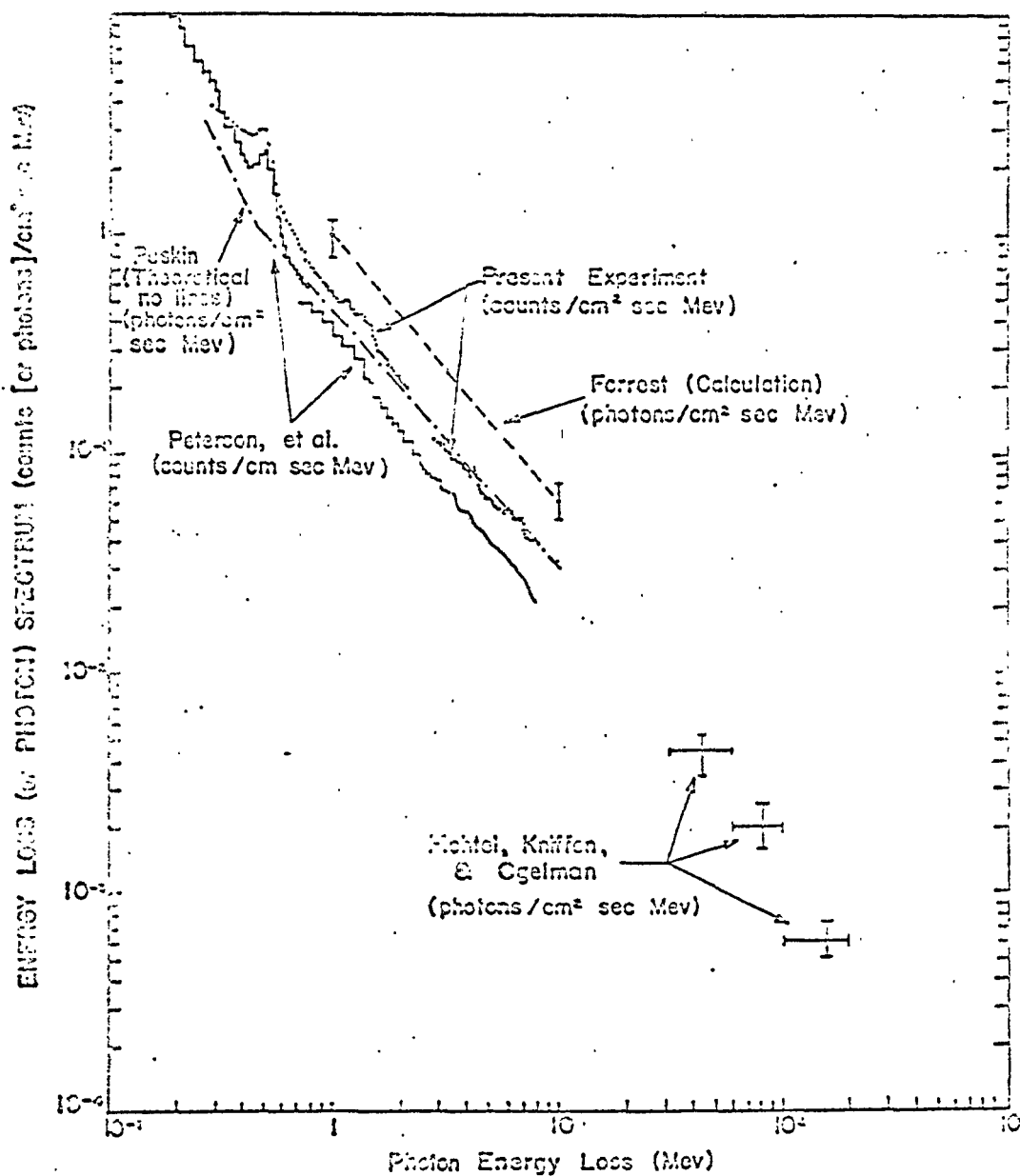


Figure D-1. Measured and calculated results for the atmospheric gamma ray spectrum at balloon altitudes (3.5 g/cm^2 , $\lambda_m = 40^\circ\text{N}$). Note that the present experiment and the results of PETERSON et al. (1966) are pulse height spectra (counts/cm² sec MeV) corrected to 3.5 g/cm^2 and $\lambda = 40^\circ\text{N}$, while the remaining results represent true photon flux spectra (photons/cm² sec MeV). Note that the curve of FORREST (1969) is valid for zero g/cm² depth.

be very close to the true gamma ray spectrum because the detector efficiency of their 3" x 3" NaI scintillation counter is high for these energies. If the detector response is used to unfold their energy loss spectrum, the net result will be a hardening of their energy loss spectrum. A crude unfolding of PETERSON'S spectrum was performed by FORREST (1969) using a generated response matrix for a 3" x 3" NaI detector. The spectrum obtained from this unfolding process when extrapolated to zero g/cm² was calculated to be

$$dN/dE_{\gamma} = (1.0 \pm 0.2) E_{\gamma}^{-(1.2 \pm 0.2)} \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ MeV}^{-1}$$

This calculated photon spectrum is indicated in Figure D-1 as a dashed line.

PUSKIN (1970) has also made theoretical calculations of the expected atmospheric gamma ray spectrum valid at an atmospheric depth of 3.5 g/cm² and geomagnetic latitude of 41°N. The reader is referred to PUSKIN'S report for details of these calculations. His calculations for the continuum portion of the total atmospheric spectrum are well fit by the function $dN/dE_{\gamma} \sim 0.25 E_{\gamma}^{-2.0}$ photons cm⁻² sec⁻¹ MeV⁻¹ below 500 keV, and by $dN/dE_{\gamma} \sim 0.47 E_{\gamma}^{-1.17}$ photons cm⁻² sec⁻¹ MeV⁻¹ above 500 keV. These curves are plotted in Figure D-1 as the dot-dashed line. Note that this curve does not include the 0.5 MeV line contribution which he also calculates. Using a generated response matrix for a 3" x 3" NaI crystal he was able to obtain agreement with PETERSON'S measured energy loss spectrum from his theoretical calculated atmospheric photon spectrum. This calculation included the contribution from extraterrestrial primary gamma rays as measured by METZGER et al. (1964).

In addition to the continuum spectrum and 0.5 MeV annihilation line feature, PUSKIN also predicts the presence

of a line at 6.13 MeV from the fast neutron inelastic scattering reaction $O^{16}(n,n')O^{16*}$ with subsequent deexcitation of the excited O^{16} nucleus. A similar process for N^{14} in the atmosphere should produce much less intense lines. He calculates the strength of the O^{16} line to be $I(6.13) \sim 6.4 \times 10^{-3}$ photons $cm^{-2} sec^{-1}$. Assuming isotropy for this flux, and using an isotropic geometry factor of $G_0 = 570 cm^2$ for the present detector and a photopeak efficiency = 0.80 at 6.13 MeV, we would expect a counting rate in the detector of 1.1 counts/sec due to this line. This should be a measurable effect in the large spectrometer.

The results obtained by PETERSON were performed with a 3" x 3" crystal having nearly isotropic response, and hence their flux represents an equivalent omnidirectional flux. The Monte Carlo calculations of the production of secondary gamma rays in the atmosphere from 0.1 - 10 MeV by PUSKIN (1970) show great anisotropy in this radiation. His calculations show that the gamma rays resulting from bremsstrahlung of cosmic ray electrons in the atmosphere (which represent $\sim 84\%$ of the total gamma ray flux) are highly anisotropic from 0.1 to 10 MeV. At $3.5 g/cm^2$ atmospheric depth the ratio of upward moving to downward moving photons varies from $\sim 4:1$ at 500 keV to $\sim 8:1$ at 10 MeV. At the 0.5 MeV annihilation line the calculated up-down asymmetry is ~ 2.3 (PUSKIN, 1970). He also predicts that the downward flux will vary roughly as $\sec \theta$, where θ is the zenith angle measured from the vertical.

This same type of asymmetry in the atmospheric flux has been experimentally observed above 100 MeV by FICHTEL et al. (1969). They observed a $\sec \theta$ rise from $\theta = 0^\circ$ to a maximum at $\theta = 90^\circ$ and a decline from $\theta = 90^\circ$ to 180° . At $\theta = 180^\circ$ the directional flux is nearly equal to the value

at $\theta = 0$. Hence, at energies >100 MeV the majority of the atmospheric gamma ray flux comes from the horizon direction. This type of anisotropy is important in determining background contributions for directional detectors flown at high altitudes.

The measured spectrum for the present detector as obtained on flight 558P is also shown in Figure D-1. This spectrum represents the measured energy loss spectrum corrected for deadtime losses and the attenuation in the surrounding materials. Since flight 558P floated at an atmospheric depth of ~ 3.5 g/cm² at an approximate geomagnetic latitude of 40°N, the spectrum is directly comparable to that of PETERSON et al. The line contributions from 1.1 to 1.5 MeV in the present spectrum are due to the Co⁶⁰ in-flight calibration source plus the K⁴⁰ (1.46 MeV) background line intrinsic to the detector. The enhancements at energies of ~ 4.3 , 6.1, and 6.8 MeV appear to be real effects. They have not been investigated further as yet. As Figure D-1 shows, the energy loss spectrum for the present detector is somewhat flatter than that of PETERSON. This is to be expected because of the increased high energy efficiency of the large spectrometer over the 3" x 3" NaI detector. The energy loss spectrum of the present detector should give a closer approximation to the true atmospheric photon spectrum than PETERSON'S measurement.

The intensity in the peak at 0.5 MeV for the present experiment was determined by using a computer fitting routine. This program fitted the continuum on either side of the peak with a two exponential function. This function was used to subtract the continuum from the total in the peak region. The remainder was then fit by a Gaussian function and the best fit area taken as the peak counting rate. This rate

was then corrected for deadtime and attenuation losses. Using a $G_0 = 570 \text{ cm}^2$, and a photopeak efficiency of $\epsilon_{pp} = 0.79$ at 0.5 MeV, the resulting equivalent isotropic 0.5 MeV line flux was found to be $0.17 \text{ photons cm}^{-2}\text{sec}^{-1}$ at 3.5 g/cm^2 atmospheric depth. This is in excellent agreement with the earlier measurements of CHUPP et al. (1969).

2. Neutron Background Effects

Any scintillation detector flown at balloon altitudes will actually measure a "neutral" energy loss spectrum. Since neutrons escape detection by the charged particle shield, they can add an unwanted contribution to the desired pure gamma ray spectrum. These neutrons, through various nuclear interactions in the crystal, can lead to gamma rays and other detectable particles which may distort the true gamma ray spectrum. If the neutron contribution to the measured spectrum is large, the analysis of the experimental results becomes much more difficult, and the assumption that one has measured a pure gamma ray spectrum is greatly in error. For this reason the background effects in the crystal due to the ambient atmospheric neutrons are considered.

The major processes by which neutrons can produce gamma ray events in the detector are (1) gamma rays produced in NaI by atmospheric thermal neutrons, (2) gamma rays from star-producing neutron reactions in the NaI, (3) events due to the interaction of fast neutrons in the NaI, (4) production of 2.23 MeV gamma rays by moderation and subsequent capture of fast neutrons in the charged particle shield, and (5) production of radioactive gamma ray emitters by activation of the crystal or surrounding materials. Processes (1), (2), and (3) contribute to the gamma ray continuum while

processes (4) and (5) line contributions.

Calculations of the relative contributions expected from each of these processes were made for a geomagnetic latitude $\lambda \sim 40^\circ\text{N}$ and atmospheric depth of $\sim 4 \text{ g/cm}^2$ (the approximate parameters for the balloon flight of June 7, 1970). Each process is discussed briefly and the method of calculation presented.

(1) Thermal neutron capture reactions in the Na and I of the detector have rather large cross sections and produce a complex spectrum of gamma rays resulting from the subsequent decay of the excited nuclei. This is particularly true for Na, for which a large number of possible gamma ray lines can result above 100 keV (GROSHEV et al., 1959). The counting rate effect of such events produced by the direct interaction of the atmospheric thermal neutron flux with the detector was estimated by the method used by JONES (1961). Using the atmospheric neutron capture rate measurements of HAYMES and KORFF (1960), he was able to calculate the capture rate in his balloon-borne GeI phoswich detector at a latitude $\lambda = 41^\circ\text{N}$ and atmospheric depth $\sim 5.4 \text{ g/cm}^2$. The calculations were based on the fact that the detectors in both experiments (BF_3 proportional counters in the case of HAYMES and KORFF) were "1/v" absorbers (in other words, the capture cross section, $\sigma_c \sim 1/v$ for neutrons of near thermal energy). This allowed the counting rates of HAYMES and KORFF to be readily converted to counting rates in his detector.

The same method was used for the present NaI detector. The measurements of HAYMES and KORFF, made at a geomagnetic latitude of 55°N , were reduced by a factor of 1.3 (SOBERMAN, 1956) to correct them to a geomagnetic latitude of 40°N . Thermal neutron cross sections of 7.0 barns for I and 0.505 barns for Na (HUGHES and SCHWARTZ, 1958; GROSHEV

et al., 1959) imply a 7.51 barns/molecule thermal neutron capture cross section in NaI. Using this cross section an average effective area for thermal neutron capture of $\sim 430 \text{ cm}^2$ was calculated for the present detector (assuming an effective thickness of $\sim 12.7 \text{ cm}$ and $G_0 = 570 \text{ cm}^2$).

The calculated counting rate in the NaI crystal due to thermal neutron capture at 3.5 g/cm^2 atmospheric depth and $\lambda = 40^\circ\text{N}$ was found to be $\sim 7 \text{ counts/sec}$, or $\sim 0.5\%$ of the total neutral counting rate observed above 250 keV. It should be pointed out here that the calculation assumes that every neutron capture produces a gamma ray in this energy region and that every gamma ray was detected in the crystal. Hence, the 0.5% figure is an overestimate of the effect. This result agrees roughly with the results of KASTURIRANGAN (1971), who calculated a 3% effect for a 1" diameter x 1/2" thick NaI spectrometer at 7.0 g/cm^2 atmospheric depth and for equatorial latitudes.

(2) The contribution from star-producing neutron interactions has been estimated by JONES (1961) and KASTURIRANGAN (1971) and found to be a negligible effect in their respective detectors. Calculations were made for the present detector by correcting the star-producing atmospheric neutron measurements of LORD (1951), made at a residual depth of 45 g/cm^2 and geomagnetic latitude of 55°N to a geomagnetic latitude of 41°N and atmospheric depth of 3.5 g/cm^2 . The atmospheric depth correction was evaluated from the fast neutron flux versus pressure measurements of HAYMES (1964) at 41°N latitude. A latitude correction of 0.44 obtained from HOLT et al. (1966) was used to correct the neutron flux from $\lambda = 55^\circ\text{N}$ to $\lambda = 41^\circ\text{N}$. Geometrical cross sections of 1.49 barns for I^{127} (LORD, 1951) and 0.73 barn for Na^{23} were used in calculating the detector sensitivity.

The results show that this effect is $\sim 1\%$ of the total neutral counting rate at 3.5 g/cm^2 atmospheric depth.

(3) Another neutron-induced effect is the direct interaction of fast atmospheric neutrons in the crystal leading to gamma rays and charged particle products which yield events in the crystal. To estimate the contribution of this process the following equation was evaluated,

$$R \text{ (counts/sec)} = \bar{\epsilon} \int_{E_{\min}}^{E_{\max}} \frac{dN(E)}{dE} \cdot A(E) dE,$$

where $\bar{\epsilon}$ is the average efficiency for detection of the reaction products, $dN(E)/dE$ is the energy dependent differential atmospheric fast neutron flux (neutrons/cm²sec MeV) at balloon altitudes, $A(E)$ is the energy dependent effective cross section (cm²) for fast neutron interactions in the NaI crystal, and $E_{\min}$ and $E_{\max}$ define the energy range of neutrons included in the calculation. For $dN(E)/dE$ the measured atmospheric fast neutron spectra of HAYMES (1964) and HESS et al. (1959) and calculations of LINGENFELTER (1963) were used. This flux was assumed to be an isotropic flux. $A(E)$ was calculated from the energy dependent non-elastic neutron reaction cross sections for NaI found in HOWERTON (1958), and an isotropic geometry factor of 570 cm^2 was used for the detector. The equation was evaluated by numerical integration for atmospheric neutrons in the range $E_{\min} = 200 \text{ KeV}$ to $E_{\max} = 100 \text{ MeV}$ using $\bar{\epsilon} \sim 0.75$.

Note that the non-elastic neutron cross sections rather than the total neutron cross sections were used. Elastic neutron scattering interactions, (n,n') , were neglected because the scattered neutron is assumed not to interact elsewhere in the crystal and hence will not produce an event.

Under these assumptions the calculated counting rate from fast neutrons of 43 counts/sec represents $\sim 3\%$ of the total expected neutral counting rate at 3.5 g/cm^2 residual depth.

(4) A rough estimate was made of the counting rate due to the production of 2.23 MeV deuteron formation gamma rays in the plastic charged particle shield from the thermal neutron capture reaction $p + n \rightarrow H^2 + \gamma$. CHUPP et al. (1968) have studied this problem and find that production due to ambient atmospheric thermal neutrons is the major contributor, as opposed to the local production of thermal neutrons and subsequent capture.

The plastic scintillator was assumed to act as a "1/v" absorber. By comparison of the cross section used by HAYNES and KORFF (1960) to that calculated for my charged particle shield, their experimental thermal neutron capture results were corrected to give a maximum production rate of 2.23 MeV gamma rays in the plastic scintillator. Using $\sigma_c \sim 0.32$ barn for the hydrogen in the scintillator and an isotropic geometry factor of 2150 cm^2 for the plastic scintillator shield, the effective area for neutron capture in the shield was found to be 40 cm^2 . The production rate was calculated to be 0.615 (2.23 MeV photons/sec) in the entire shield. The photons so produced are emitted isotropically into a 4π solid angle. Assuming that the detector intercepts an average solid angle of $\pi \text{ sr}$ for any point in the shield, we find that 0.15 (2.23 MeV photons/sec) are incident on the detector. With a photopeak efficiency of 0.43 at 2.2 MeV, we expect that a line contribution at 2.23 MeV of 30.666 counts/sec should result from thermal neutron capture in the plastic shield.

(5) In addition to the above process, gamma ray line contributions at numerous energies can be produced through activation of the NaI crystal itself or surrounding mass by incident neutrons and charged particles which produce radioactive species. These nuclides then decay at their characteristic decay rate producing contamination gamma ray events in the crystal. An example of a neutron-induced reaction is the production of 0.5 MeV gamma rays from the reaction $^{127}_{53}\text{I}(n,2n)^{126}_{53}\text{I}$, followed by the positron decay of the $^{126}_{53}\text{I}$ with a 13.2 day half life. This would actually produce a continuum contribution due to the energy loss of the positron. This does not appear to be a significant process for a balloon flight of ~ 8 hrs duration because of its low production rate and long half life. Other such reactions are $^{127}_{53}\text{I}(n,\gamma)^{128}_{53}\text{I}$ and $^{23}_{11}\text{Na}(n,\gamma)^{24}_{11}\text{Na}$ in the crystal, and the $^{27}_{13}\text{Al}(n,\alpha)^{24}_{11}\text{Na}$ reaction in the aluminum of the surrounding gondola frame and electronics. The $^{24}_{11}\text{Na}$ decays via β^- emission with 99% of the decays resulting in prompt 1.37 MeV and 2.75 MeV gamma rays emitted by the daughter nucleus $^{24}_{12}\text{Mg}$. $^{128}_{53}\text{I}$ decays by β^- emission leading to $^{128}_{54}\text{Xe}$ which yields a 0.455 MeV prompt gamma ray in 15% of the cases.

In addition to neutron-induced reactions, charged particle reactions (predominately proton-induced) can lead to radioactive species. These interactions could provide the dominant contribution since the charged particle fluxes are much higher than the neutral fluxes at balloon altitudes. Although the charged particle is vetoed by the charged particle shield, the radioactive nuclide it produces in the crystal will decay at a later time giving measurable gamma ray events. Such activation effects have been observed in satellite experiments which pass through the inner radiation

belt (PETERSON, 1965; PETERSON et al., 1968) where the proton flux is very high. Fluxes of similar particles are much lower in the earth's atmosphere.

In balloon-borne experiments contamination line contributions have been seen in these experiments using large, massive active or passive shields surrounding the detector. A number of monoenergetic line contributions were also observed in a 15.3 cm^2 Ge(Li) solid state detector (WOMACK and OVERBECK, 1970) flown at a depth of 4.7 g/cm^2 . These lines were attributed to the production of radioactive nuclides from (n, γ) reactions in the Ge. The present experiment has no massive shield near the detector. In any event, calculations of these effects are quite complex owing to the uncertain knowledge of cross sections, particle fluxes, and physical geometries. Only very crude estimates could be obtained. Calculations of charged particle induced effects were not performed for the present detector.

An additional source of background lines is the radioactive decay of contaminants intrinsic to the detector and surrounding phototube materials. In the present detector this effect will probably be the most significant contributor to background line radiation in the crystal. The naturally occurring K^{40} and Th^{228} nuclides in the phototube materials emit gamma rays at energies of 1.46 and 2.62 MeV respectively. These lines are always observable in a spectrum taken with the present detector. They are expected to represent a several percent effect above the continuum atmospheric background in their respective photopeak regions and may be observable in the gamma ray spectrum at balloon altitudes. That this is the case is seen in Figure D-1 from the measured energy loss spectrum in the present detector from flight 558P. The enhancement in the energy interval

from 1.1 MeV - 1.5 MeV is due to the contribution at 1.47 MeV from the K^{40} contaminant plus the leakage spectrum of the Co^{60} calibration source.

By combining the results of this section we see that neutron effects in the present crystal should be $\lesssim 5\%$ of the total neutral counting rate above 250 keV at a geomagnetic latitude of $40^\circ N$ and atmospheric depth of 3.5 g/cm^2 . Hence neutron effects should represent no serious limitation to the present pulsar search analysis. They affect this search only in that they increase the background counting rate, which makes it more difficult to observe small pulsar signals.

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APPENDIX E

APPARENT PERIOD CHANGES FOR NP 0532 FOR BALLOON
LOCATION ON JUNE 7, 19701. Introduction

In this appendix the apparent period changes of pulsar NP 0532 are discussed and these changes are calculated for the day of flight 558P (June 7, 1970).

In general, an observer positioned somewhere on the earth will observe a different frequency of pulsation for a pulsar than an observer in the rest frame of the pulsar. It has become standard practice to transform the observed period not to the rest frame of the source, but to the period value as would be observed at the solar system barycenter. We shall follow this practice here.

The difference takes the form of a Doppler shift in observed frequency of emission due to the relative motion of the source and observer. Since this relative motion occurs at a speed much less than the speed of light, non-relativistic equations are valid for the calculations. In addition to this Doppler correction, pulsars themselves appear to be continuously slowing down in their own rest frames. For NP 0532 this slowdown rate has been measured by a number of experimenters (see, for example, FISHMAN et al., 1969 and BOYNTON et al., 1969) resulting in a value of

$$\dot{P}/dt = +36.52 \text{ nsec/day.}$$

Combining these effects yields an ephemeris of period values for any given day. Since the pulsar analysis requires a tracking of the apparent period at the detector location, knowledge of the expected apparent period change during the flight is quite critical.

2. The Period Calculations

The following definitions are made for clarity in understanding the calculations:

- i. Barycentric Period = period measured by an observer at the center of gravity of the solar system (P_B).
- ii. Heliocentric Period = period as measured in the Sun-centered coordinate system (P_O).
- iii. Geocentric Period = period as measured in the Earth-centered coordinate system (P_G).
- iv. Apparent Pulsar Period = period as measured at the balloon payload (P_A).

Given a barycentric period value at a given epoch during the flight, the problem is to calculate the change in apparent period value at the balloon location during the flight. The total period transformation from barycentric to apparent period was carried out in four steps. The corrections obtained for each step are added to give the total transformation. The four basic steps are:

Step 1: Conversion of barycentric period to heliocentric period.

Step 2: Correction of barycentric period for true pulsar slowdown.

Step 3: Conversion of heliocentric period to geocentric period.

Step 4: Conversion of geocentric period to apparent period.

3. Barycentric to Heliocentric Correction

The barycentric to heliocentric correction term was determined to be negligible for the present analysis as is seen from the following arguments. An idea of the magnitude of this correction is obtained from an application of the Doppler shift equations to the relative motion of the Sun and the solar system barycenter. The non-relativistic first order Doppler shift equation to be used for this correction (and all Doppler corrections) is given by

$$f = f_0 \left(1 - \frac{v}{c}\right), \quad \text{E-1}$$

where

f_0 = frequency of emission in rest frame of source,

f = observed frequency in frame of moving observer,

v = relative speed between source and observer

(projection of observer's velocity along the line joining the source to observer).

Since $f = \frac{1}{P}$, where P = period, we obtain

$$\frac{1}{P} = \left(\frac{1}{P_0}\right) \left(1 - v/c\right)$$

or

$$\Delta P = P - P_0 = \frac{v}{c} P \approx \frac{v}{c} P_0. \quad \text{E-2}$$

The last approximation is valid here because, as the results of the calculations will show, the difference between P and P_0 is of the order of 1 part in 10^4 ($\Delta P/P_0 \sim 1/10^4$). The error resulting from this approximation thus gives a completely negligible error in any of the correction calculations to follow (error always < 1 nsec).

To obtain the barycentric to heliocentric correction we require the projection of the Sun's orbital velocity about the barycenter in the direction of the Crab Nebula, as measured in the barycentric coordinate system. This is pictured in Figure E-1, where V_{SC} is the quantity of interest. The determination of the position of the barycenter with respect to the Sun is a quite complex problem due to the fact that the planetary orbits are elliptical, do not all lie in a single plane and have widely varying orbital periods. To simplify this approximate calculation, we make the following assumptions.

1. Assume that, to first order, only Jupiter and the Sun are required in the calculation of the barycenter position.
2. Assume that Jupiter, the Sun, and the Crab Nebula all move in the same plane.
3. Assume that Jupiter's orbit is circular (eccentricity of Jupiter's orbit = 0).

These assumptions imply that the Sun moves in a circular orbit about the barycenter with average orbital radius, R_{SB} (distance of barycenter from the Sun), and with an orbital period $\sim T_{JUPITER}$. Using the masses of the Sun and Jupiter as tabulated in SMART (1965), we obtain

$$R_{SB} \sim 7.43 \times 10^5 \text{ km}$$

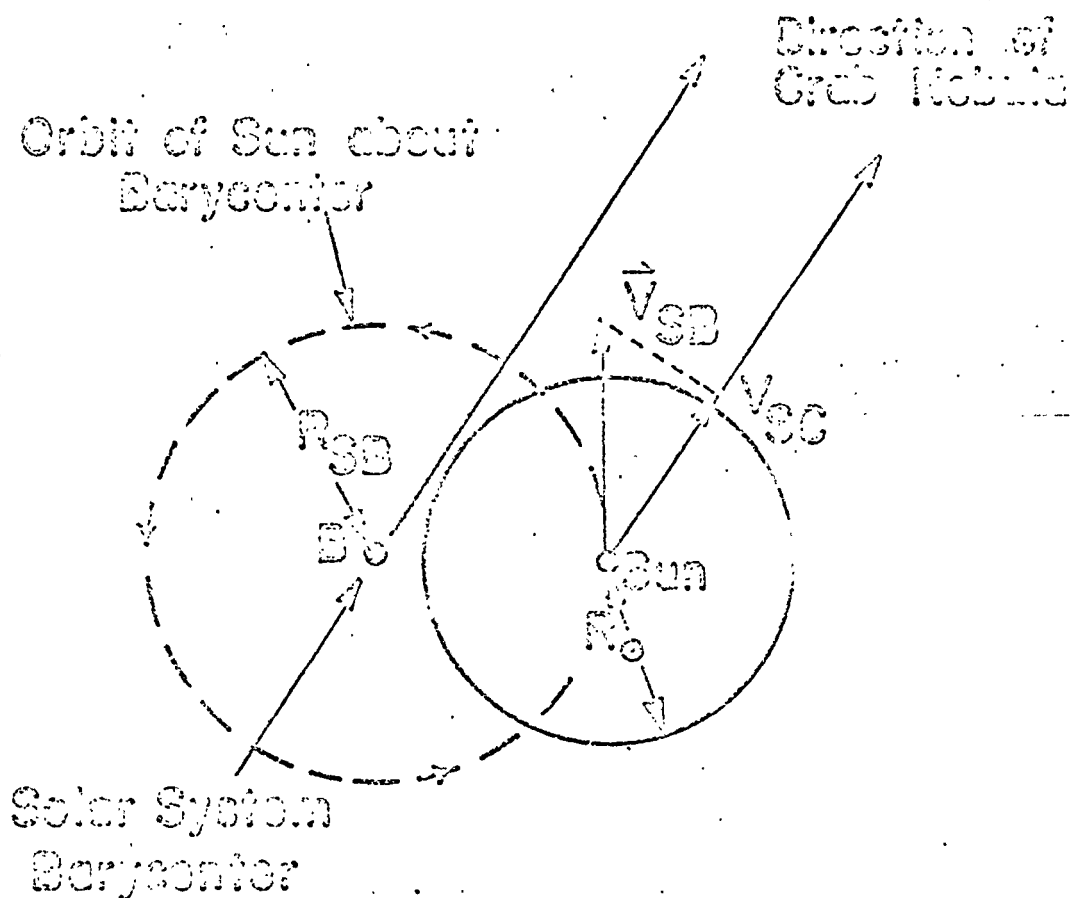


Figure E-1. Sketch of coordinates for barycentric to heliocentric period transformation. The solar system barycenter is calculated by assuming that the Sun and Jupiter are the only contributors to its position. Under this approximation, V_{SB} is the constant orbital speed of the Sun in its circular orbit about the barycenter.

Under these approximations, the position of the barycenter is slightly more than one Solar radius from the Sun's center (since $R_{\odot} \sim 6.96 \times 10^5$ km). Under the third assumption we find that $T_{SB} \sim 11.86$ tropical years $= 3.74 \times 10^8$ sec. Since $V_{SB} = 2\pi R_{SB}/T_{SB}$ for a circular orbit we get $V_{SB} \sim 1.25 \times 10^{-2}$ km/sec. The largest correction occurs when the Sun is moving directly away from or toward the position of the Crab Nebula. At these times the velocity projection is equal to $\pm V_{SB}$. Hence, the maximum barycentric to heliocentric period correction becomes

$$\Delta P_{HB}(\text{max}) \sim \frac{V_{SB} P_B}{c}$$

Using $P_B = 33.1$ ms we obtain $\Delta P_{HB} \sim 1.4$ ns, with much smaller changes in ΔP_{HB} over the course of one day. This order of magnitude correction is included in the ± 5 ns error to be assigned to the final results below and is therefore neglected. The heliocentric period, $P_{\odot}$, is thus considered to have the same value as the barycentric period for the present analysis.

The apparent period as a function of universal time can be expressed in terms of the remaining three corrections as follows

$$P_A(t) = \Delta P_1(t) + \Delta P_2(t) + \Delta P_3(t) + P_{\odot} \quad , \quad \text{E-3}$$

where

$\Delta P_1(t)$ = correction from heliocentric to geocentric period,

$\Delta P_2(t)$ = correction from geocentric to apparent period,

and $\Delta P_3(t)$ = true pulsar slowdown correction in barycentric (or heliocentric) system.

4. Intrinsic Pulsar Slowdown Referred to Barycenter

The expression $P_0(t) = P_0 + \Delta P_3(t)$ represents the true heliocentric pulsar period as a function of time. As mentioned earlier the term $\Delta P_3(t)$ has the measured average value 36.52 ns/day. Hence, $\Delta P_3(t)$ has the form

$$\Delta P_3(t) = (1.52) (t - t_0) \text{ nanoseconds,} \quad \text{E-4}$$

where t is measured in hrs and t_0 is an arbitrarily chosen reference time (in hrs) for zero pulsar slowdown correction. t_0 is the epoch at which the heliocentric period, $P_0(t_0)$, is assumed to be known, and was chosen to be $t_0 = 15^h 50^m 30^s$ UT on June 7, 1970.

The remaining correction terms are treated separately and can be expressed as follows, using the non-relativistic first order Doppler shift equation E-2:

$$\Delta P_{1,2}(t) = \frac{V(t)_{1,2}}{c} P_0. \quad \text{E-5}$$

It only remains to calculate the velocity for each correction term.

5. Heliocentric to Geocentric Correction

To calculate the correction from the Sun-centered coordinate system to Earth-centered system, we need to know the projection of the Earth's velocity, $V_1(t)$, along the line joining the Earth to the position of NP-0532. For convenience, the parameters needed in this calculation are expressed in geocentric coordinates. This exact problem has been solved in SMART (pp. 214-215), and using his results

(and adopting his notation) we obtain for this velocity projection

$$V_1(t) = \frac{2\pi a \cos\beta}{T(1-e^2)^{1/2}} \left\{ \sin [\theta(t)-\lambda] - e \sin (\tilde{\omega}-\lambda) \right\}, \quad E-6$$

where

a = semi-major axis of Earth's orbit about the Sun,

T = period of Earth's orbit about the Sun,

e = eccentricity of Earth's orbit,

β = latitude of NP 0532 as measured in geocentric coordinate system,

λ = longitude of NP 0532 as measured in geocentric coordinate system,

$\tilde{\omega}$ = longitude of the Earth's perihelion on the ecliptic plane as measured in the geocentric coordinate system, and

$\theta(t)$ = geocentric true Solar longitude.

The relationship of the various angles and distances used in this calculation is shown in Figures E-2 and E-3.

The commonly given coordinates of celestial bodies are the right ascension (RA) and declination (δ) as measured on the standard celestial sphere (celestial equator parallel to the Earth's equator) (SMART, p. 37). Given the RA and of the source position, we can calculate the equivalent celestial latitude and longitude (using the ecliptic plane as a great circle) β and λ respectively, from the formulae (SMART, p. 40)

$$\cos(\beta) \cos(\lambda) = \cos(\delta) \cos(RA) \quad E-7$$

$$\cos(\beta) \sin(\lambda) = \sin(\delta) \sin(\epsilon) + \cos(\delta) \cos(\epsilon) \cos(RA).$$

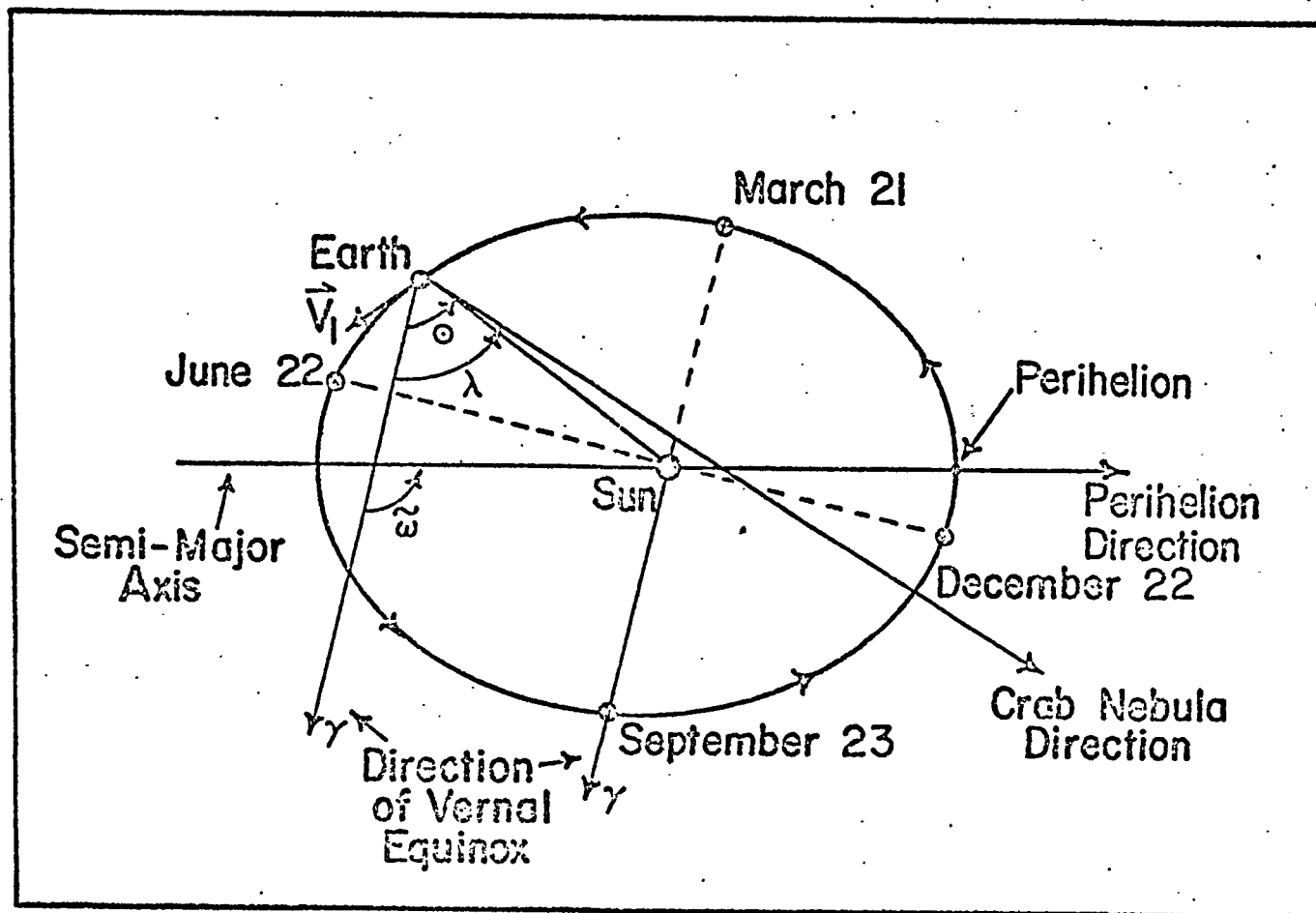


Figure E-2. Sketch of coordinates and angles for heliocentric to geocentric period transformation. The drawing roughly depicts the situation valid for flight 558P (June 7, 1970).

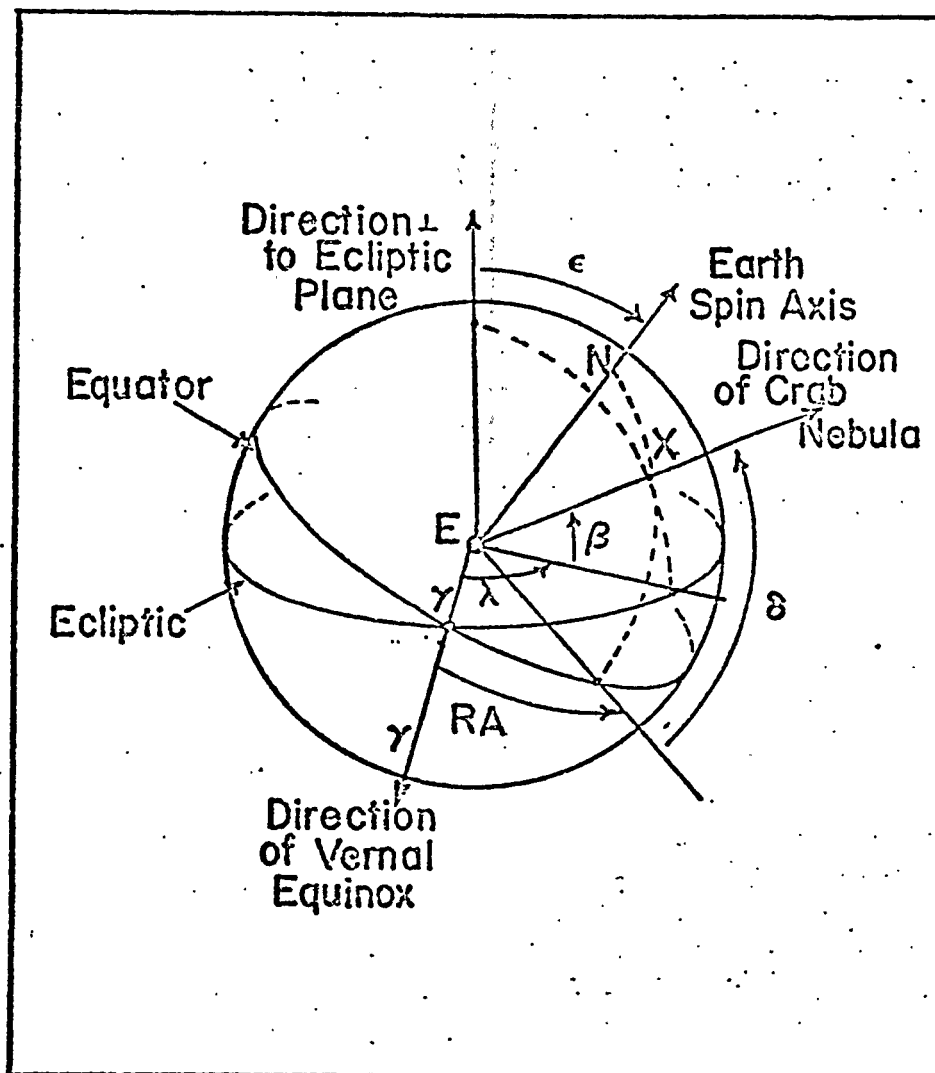


Figure E-3. Sketch of position of Crab Nebula as expressed in two Earth-centered coordinate systems. One uses the equator as the fundamental great circle with λ and β being the longitude and latitude of the star's position. The second has the ecliptic as the fundamental great circle with the right ascension (RA) and declination (δ) being the angular coordinates. Both systems use the vernal equinox as principal reference point.

Combining equations E-5 and E-6 gives for the heliocentric to geocentric correction term

$$\Delta P_1(t) = \frac{2\pi a \cos \beta}{cT(1-e^2)^{1/2}} P_0 \{ \sin[\theta(t)-\lambda] - e \sin(\tilde{\omega}-\lambda) \}. \quad E-8$$

λ and β are evaluated from equations E-7. In this formula the minus sign was chosen to give $\Delta P_1(t) < 0$ for $V_1(t) > 0$ as required for the period change due to a Doppler shift.

6. Geocentric to Apparent Correction

The correction for geocentric to apparent period contains the Doppler shift due to the diurnal motion of the Earth about its spin axis. The quantity needed for use in equation E-5 is $V_2(t)$, the component of velocity of an observer at a point on the Earth's surface in the direction of NP 0532. A diagram of the pertinent coordinates is shown in Figure E-4.

Once again SMART (pp. 216-217) has considered this problem in detail, and the resulting velocity component, $V_2(t)$, is found to be

$$V_2(t) = \frac{2\pi (R_e + h)}{T_e} \cos(\phi) \cos(\delta) \sin [H(t)], \quad E-9$$

where R_e = mean equatorial radius of the Earth,

h = float altitude of the balloon above the Earth's surface,

T_e = rotational period of the Earth,

ϕ = latitude of the balloon,

δ = declination of NP 0532, and

$H(t)$ = local hour angle of NP 0532 (measured with respect to the meridian of the balloon).

Using equation E-5 we obtain

$$\Delta P_2(t) = \frac{2\pi (R_e + h) P_0}{c T_e} \cos(\phi) \cos(\delta) \sin [H(t)]. \quad E-10$$

(The replacement of R_e by $(R_e + h)$ in SMART's equation (51) (p. 217) accounts for the fact that the observer is a distance h above the Earth's surface. His equation (51) is valid for an observer on the surface of the Earth).

This equation assumes that the observer is fixed at the same latitude, longitude, and altitude during the flight. The latitude, longitude, and altitude for the present calculations were arbitrarily chosen to be those values for the balloon location at 15^h 50^m 00^s UT. The balloon latitude varied from 31.0°N to 31.5°N during float, which represents a 0.5% correction in equation E-10. The float altitude fluctuated from 38.45 km to 37.40 km which represents a $\ll 0.1\%$ perturbation to the results. Both these perturbations are completely negligible. The largest error in this assumption results from the balloon drift in longitude throughout the flight. During the 4.5 hr interval at float for flight 558P, the balloon longitude changed from 96.3°W to 100.5°W longitude. This westerly drift in longitude across the Earth has the effect of reducing the tangential velocity at the position specified.

In equation E-9, $V_2(t)$ is the tangential velocity directed eastward at the latitude, ϕ , and altitude, h , assuming that there was no balloon drift in longitude. The westerly balloon drift has the effect of reducing this tangential velocity by an amount equal to the longitudinal balloon drift speed, assuming that the altitude is approximately constant. Including this effect, the corrected $V_2(t)$ would be

$$V_2^i(t) = \left\{ \frac{2\pi (R_e + h)}{T_e} - V_{DR} \right\} \cos(\phi) \cos(\delta) \sin [H(t)],$$

and the period correction including the longitudinal balloon motion becomes

$$\Delta P_2(t) = \left\{ \frac{2\pi (R_e + h)}{T_e} - V_{DR} \right\} \frac{P_0}{c} \cos(\phi) \cos(\delta) \sin [H(t)].$$

E-11

Using the post-flight balloon position data supplied by NCAR, the average longitudinal balloon drift speed was calculated to be $V_{DR} = 2.47 \times 10^{-2}$ km/sec.

The total period correction is obtained by combining equations E-4, E-8, and E-11 in equation E-3. A computer program was developed to perform these calculations. A listing of this program is given at the end of this appendix. The coordinates of the location of pulsar NP 0532 were taken to be those of the south-preceding central star of the Crab Nebula as given by MINKOWSKI (1968). For the day of the flight, the value of the true Solar longitude at $00^h 00^m 00^s$ UT was obtained from Astronomical Papers, Vol. XIV, p. 625. All further values of $\theta(t)$ were generated in the program.

The results of these calculations for a time interval bracketing the float portion of the flight are shown in Figure E-5. The calculations were made in time increments of 10 minutes. As Figure E-5 shows, the heliocentric to geocentric period correction over this time period is well approximated by a straight line with a slope of $dP/dt \approx -2.34$ nsec/hr. The total correction shown in Figure A-5 shows a sinusoidal domination of the total correction vs. time curve.

To obtain the absolute apparent period value for the day of the flight, we need to know the barycentric period, P_0 , for a given epoch. This value was obtained as follows. As

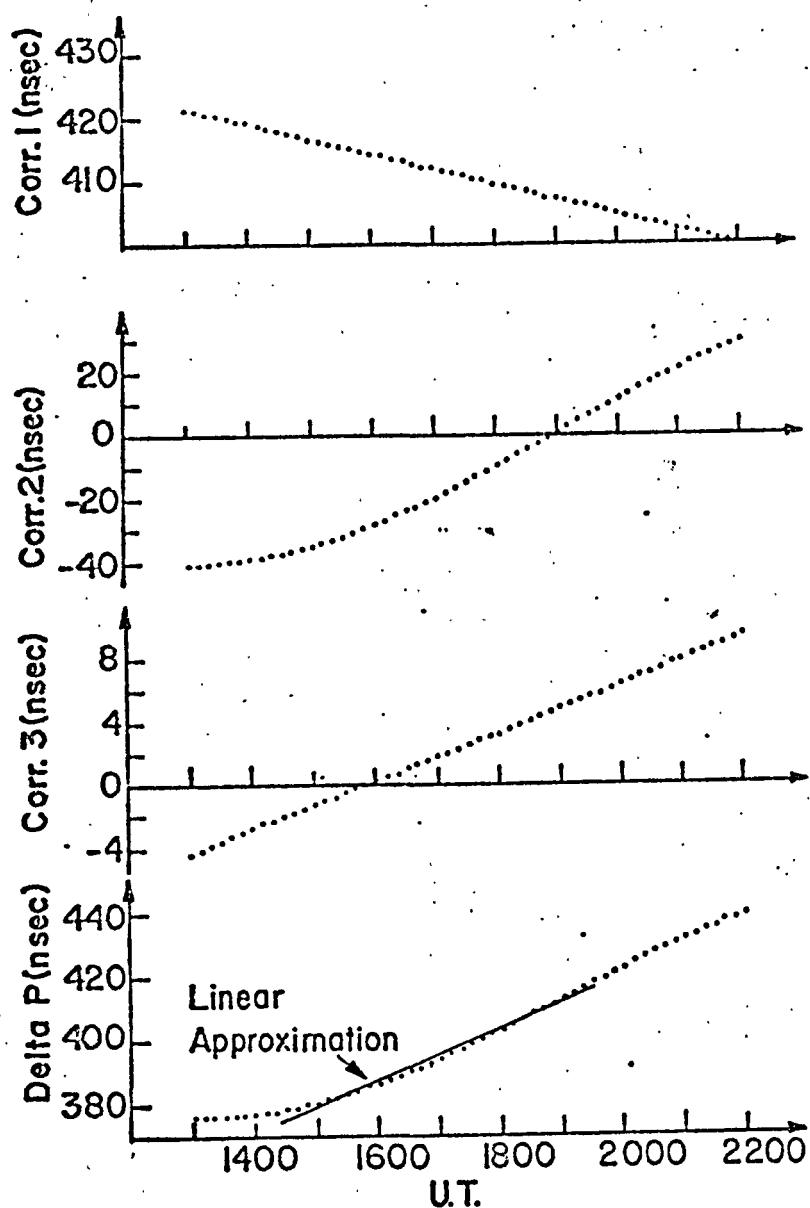


Figure E-5. Period corrections for NP 0532 on June 7, 1970. The heliocentric to geocentric, geocentric to apparent, and true pulsar slowdown corrections are given by CORR.1, CORR 2, and CORR 3 respectively. Delta P is the total correction (CORR 1 + CORR 2 + CORR 3) to be applied to the barycentric period to obtain the apparent period. The solid line is the best least square linear fit to the data from 1430 UT to 1910 UT.

an independent check of our calculations, apparent period and absolute main pulse arrival time information for the optical emission of NP 0532 were provided for us by Dr. C. Papaliolios at Harvard University for the epoch of the flight. These calculations were made for the balloon location at a reference time of $15^{\text{h}} 50^{\text{m}} 30^{\text{s}}$ UT. This data included the apparent period value at one minute increments from $15^{\text{h}} 00^{\text{m}} 00^{\text{s}}$ UT to $16^{\text{h}} 00^{\text{m}} 00^{\text{s}}$, and the closest optical main pulse arrival time to $15^{\text{h}} 50^{\text{m}} 30^{\text{s}}$ UT. The Harvard results indicated that a main optical pulse occurred at $15^{\text{h}} 50^{\text{m}} (29.9956 \pm 0.0003)$ sec UT. To obtain the barycentric period at the reference time of $15^{\text{h}} 50^{\text{m}} 30^{\text{s}}$, I normalized my results to the Harvard period value at $15^{\text{h}} 50^{\text{m}} 00^{\text{s}}$ UT. This normalization yielded a heliocentric (barycentric) period

$$P_0 = 33.111920 \text{ nsec}$$

at $15^{\text{h}} 50^{\text{m}} 00^{\text{s}}$ UT. Since the period rate of change is $\ll 1$ nsec/min we can use this value as the barycentric period at the epoch $15^{\text{h}} 50^{\text{m}} 30^{\text{s}}$. Combining this value of P_0 with the total correction term $\Delta P(t)$ gives the final result for the apparent pulsar period vs. time.

Data analysis requires that we track this apparent period during the observation time. In the present analysis, data from $14^{\text{h}} 32^{\text{m}} 01^{\text{s}}$ UT to $19^{\text{h}} 11^{\text{m}} 00^{\text{s}}$ UT was analyzed. Note that from Figure E-5 a linear approximation to the period change gives a fairly good fit to the total correction curve. We can write this linear fit as

$$P_A(t) = P_A(t_0) + M(t-t_0),$$

where $t_0 = 15^{\text{h}} 50^{\text{m}} 30^{\text{s}}$ UT. Thus, times earlier than t_0 are considered as negative in this fit. A least squares linear fit to $P_A(t)$ vs. t over the above time interval gives

$$P_A(t_o) = 33.112308 \pm 0.000001 \text{ ms},$$

and

$$M = (2.25 \pm 0.05) \times 10^{-9} \text{ ms/sec.}$$

as the best fit parameters. These values were then used as the optimum parameters in the final phase alignment computer program. Note that the above errors are obtained only from the least squares fitting procedure. The total error in the determination of the expected pulsar period must include the errors involved in calculating each correction term. It is not unreasonable to assume that we can calculate each term to an accuracy of 1%. If this is true, the error for each correction becomes

$$\sigma(\Delta P_1) = \pm 0.015 \text{ ns}, \sigma(\Delta P_2) = \pm 4 \text{ ns}, \sigma(\Delta P_3) = \pm 0.2 \text{ ns}.$$

These combine to give a most probable total correction error of $\sigma_{\text{tot}} = 4 \text{ ns}$. Combining this error with the fitting error expressed above, we arrive at an uncertainty of $\pm 5 \text{ ns}$ for the calculation of the apparent period value for NP 0532.

This error applies to the period value at any point during the flight.

A final comment concerns the reference time chosen in the analysis. The knowledge of the absolute starting time of the superposition analysis is important for obtaining absolute arrival time information from the data. In adding the data together, one time had to be arbitrarily chosen as the zero phase time to which all phase-aligned data is referred. The epoch $15^{\text{h}} 50^{\text{m}} 30^{\text{s}}$ was chosen above as the reference time for zero period slowdown corrections. The ninth multiscaler run was started 3 ms before this time, and all final phase plots are referred to the start of this run, at the epoch $15^{\text{h}} 50^{\text{m}} (29.9970 \pm 0.0002)^{\text{s}}$ on June 7, 1970, as the zero

phase time. Consequently, when a period value is mentioned in the text, it refers to the value at this epoch. To obtain the period at some other time during the data interval, the linear approximation developed above is used.

7. Computer Program for Period Correction Calculations ("PERIOD")

The "PERIOD" program was written to make the period correction calculations described in this appendix. The program listing which follows is rather self-explanatory. The input information used for the present correction calculations is also included in the program. The program was written in the FORTRAN language for operation on the Dartmouth Time Share System. By suitably changing the input information, the apparent period of any pulsar at any observer location on the earth can be obtained for any given day. The program generates a daily ephemeris of the apparent pulsar period.

PERIOD 01 SEP 71 16:01

```

5C  THIS PROGRAM PERFORMS A CALCULATION OF PULSAR PERIOD
    CHANGES
10C  OVER A TIME PERIOD SELECTED BY THE OPERATOR (MUST BE
15C  LESS THAN 24 HRS.). INCLUDED ARE CORRECTIONS DUE TO (A)
20C  CONVERSION OF HELIOCENTRIC TO GEOCENTRIC PERIOD, (B)
25C  CONVERSION OF GEOCENTRIC TO APPARENT PERIOD, AND (C)
30   TRUE PULSAR SLOWDOWN.
35C  INPUTS ARE (IN THE ORDER REQUESTED IN THE PROGRAM):
40
45C  RA = RIGHT ASCENSION OF SOURCE (RAD.)
50C  DECL = DECLINATION OF SOURCE (RAD.)
55C  PO = HELIOCENTRIC PERIOD AT T-0
60C  OMEGA = LONGITUDE OF EARTH PERIHELION ON ECLIPTIC (RAD.)
65C  ECL = ANGLE BETWEEN EARTH SPIN AXIS AND ECLIPTIC (RAD.)
70C  GSOLON = GEOCENTRIC SOLAR LONGITUDE AT 0 HR. UT FOR DAY
75C  OF CALCULATION (RAD.)
80C  E = EARTH'S ORBITAL ECCENTRICITY
85C  A = SEMI-MAJOR AXIS OF EARTH'S ORBIT (KM.)
90C  RADE = EARTH'S EQUATORIAL RADIUS (KM)
95C  EPER = PERIOD OF EARTH'S ORBIT (SEC.)
100C T = PERIOD OF EARTH'S ROTATION (SEC.)
105C ALAT = LATITUDE OF DETECTOR (RAD.)
107C H = ALTITUDE OF DETECTOR (KM)
108C VDR = BALLOON DRIFT SPEED (EAST = +, WEST = -) (KM/SEC)
110C RAMS = RIGHT ASCENSION OF MEAN SUN FOR DAY OF FLIGHT (RAD.)
115C XLPAL = LONGITUDE OF THE DETECTOR (RAD.)
120C PRATE = SLOWDOWN RATE OF PULSAR (MS./HR.)
125C C = SPEED OF LIGHT (KM./SEC.)
130C L,M = START AND STOP TIMES FOR CALCULATIONS (IN MULTIPLES
135C OF XX MINUTES)
140C XX = TIME INCREMENT FOR PERIOD CALC. (MIN.)
145C TSUBO = REFERENCE TIME FOR ZERO SLOWDOWN CORRECTION
150
155  DOUBLE PRECISION PO, PERIOD
160  RA = 1.44644
170  DECL = 0.383681
180  PO = 331119.230000D-04
190  OMEGA = 1.78464
200  ECL = 0.409279
210  GSOLON = 1.32325
220  E = 0.016726
230  A = 1.49674E+08
240  RADE = 6378.417
242  H = 38.4
244  VDR = 0.0247

```

```

250 EPER = 3.15581E+07
260 T = 86164.0
270 ALAT = 0.545939
280 RAMS = 1.30463
290 XLPAL = 1.67115
300 PRATE = 1.5217E-06
310 C = 299800.0
320 L = 78
330 M = 132
340 XX = 10.
350 TSUBO = 15.84167
352 WRITE (" ",20) PO
353 20FORMAT(1X,30HBARYCENTRIC PERIOD AT TSUBO = ,F14.10,
1X,5HMSEC.)
400 VORB = (2.*3.14159*A)/(EPER*SQRT(1.-E**2))
410 TANL = (SIN(DECL)*SIN(ECL) + COS(DECL)*COS(ECL)*SIN(RA))/
420& (COS(DECL)*COS(RA))
430 ALAMB = ATAN(TANL)
450 COSB = COS(DECL)*COS(RA)/COS(ALAMB)
470 TERMO = VORB*COS*PO/C
480 WRITE (" ",60) TERMO
482 60 FORMAT(1X,39HMAXIMUM PERIOD CORR.,,HELIO. TO GEO. =
483& ,F10.7, 1X,5HMSEC.)
490 TERM1 = E*SIN(OMEGA - ALAMB)
500 TERM2 = (2.*3.14159*(RADE+H)/T - VDR)*COS(ALAT)*COS(DECL)
510C W = ANG. RATE OF CHANGE IN GSOLON (RAD/MIN)
520 W = 2.*3.14159/(365.2564*24.*60)
530 PROT = TERM2*PO/C
532 WRITE (" ",65) PROT
534 65 FORMAT(1X,30HPEAK CORR., GEO. TO APPARENT = ,F10.7,1X,
535& 5HMSEC.)
540 TERM3 = RAMS - RA - XLPAL - 3.14159
550 WRITE (" ",70) TERM3
552 70 FORMAT(1X,29HTERM3 (HRANG = TERM3 + UT) = ,F8.4,1X,
7HRADIANS)
560 WRITE (" ",80)
562 80 FORMAT(/4X,2HUT,5X,7H CORR. 1,5X,7H CORR. 2,5X,7H CORR. 3,
563& 5X, 7H DELTA P,5X,6H PERIOD/)
570 DO 200 I = L,M
572 SUT = 0.
580 UT = 0.
590 Y = I.
600 SUT = SUT + 2.*3.14159*Y*XX/1440.
610 UT = 24.*SUT/(2.*3.14159)
620 LUT = UT
622 ALUT = LUT
630 XLUT = 0.
640 XLUT = ALUT*100.

```

```
650 JFUT = XLUT + (UT - ALUT)*60.
660 HRANG = SUT + TERM3
670 DELP1 = -TERMO * (SIN(GSOLOX+XX*W*Y - ALAMB) - TERM1)
680 DELP2 = PROT*SIN(HRANG)
690 DELP3 = (UT - TSUBO)*PRATE
700 DELP = DELP1 + DELP2 + DELP3
710 PERIOD = PO + DELP
720 WRITE (" ",100) JFUT,DELP1,DELP2,DELP3,DELP,PERIOD
730 100 FORMAT(1X,I6,2X,F10.7,2X,F10.7,2X,F10.7,2X,F10.7,3X
F12.8)
740 200 CONTINUE
800 STOP
810 END
```

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APPENDIX F

TIMING UNCERTAINTIES IN THE PULSAR ANALYSIS

1. Introduction

In this appendix a discussion of the timing errors encountered in performing the present analysis is presented. In particular, we will consider two topics, the synchronization accuracy required between the synthesized period signal and the pulsar signal, and the error assigned to the absolute arrival time of a gamma ray event. The requirement of precise timing in this method is so stringent that overly large synchronization errors can easily render the results unreliable. The magnitude of the uncertainty in knowledge of arrival time of a gamma ray event directly affects the amount of time detail that can be observed in the final superposition results. A large time-of-arrival uncertainty implies very little time resolution, while a small timing error allows one to observe finer detail in the pulse profiles. First, we shall develop a basic equation used to determine the synchronization accuracy needed in the present analysis. Then, timing errors which contribute to the uncertainty in the absolute time-of-arrival are presented.

2. Period Synchronization Requirements

The superposed epoch analysis method chosen for the present pulsar search has been used by numerous investigators for analyzing pulsar data. It is by far the most often used method for observing the pulsar NP 0532 in the optical and

gamma ray bands. This method requires that artificial synchronism with the period of the object must be achieved and maintained to a high degree of accuracy during the data integration time. The importance of maintaining this accurate synchronization can be seen from the following arguments. If the error in synchronism is given by ϵ_p (time error/period), and P is the true pulsar period, at the end of the data integration time, T , there will be an absolute time phase shift, Δt , given by

$$\Delta t = \frac{\epsilon_p T}{P} . \quad \text{F-1}$$

For example, if synchronism is made to a precision of 1 μ s per 33 ms period, an integration time of only $T = 33$ sec can be used before the absolute phase has drifted by ~ 1 ms. For longer integration times this synchronism must be maintained to a much higher accuracy, or the resulting phase drifting will create a smeared result. For the present experiment, these considerations imply the following constraints. The data integration time span used for the present analysis is 16,739 sec (from 14^h 32^m 01^s UT until 19^h 11^m 00^s UT). In order to keep the phase drift $\lesssim 1$ ms over this time span, we find from equation IV-1 that ϵ_p must be $\lesssim 2$ ns/period for $P = 33$ ms. The requirement that the total phase shift be $\lesssim 1$ ms is based on the calculation of the absolute time-of-arrival error given below. If the data were overlaid using the superposition analysis in one long 16,739 sec run, period synchronism would have to be maintained to better than 2 ns/period to keep the absolute phase drift $\lesssim 1$ msec during the integration time. This resolution implies a required long term time stability of 7 parts in 10^8 . In the present analysis this stability was provided by the WWV signal

recorded on the magnetic tapes during the flight. Jitter in the transit times of the WWV signals to Texas does lower the basic timing accuracy of the WWV signal as generated at the transmitting station. Even so, the long-term stability of the WWV signal as received in Texas is more than sufficient to provide the necessary timing accuracy. Note also that calculations using equation F-1 were used to justify the subdivision of the multiscalar analysis into 32 short runs, and also used to calculate the maximum allowable length of each run.

3. Uncertainty in Photon Absolute Time of Arrival

The absolute arrival time uncertainty is of great importance because its value determines how detailed a time study can be made on the data. In addition, its magnitude puts certain design constraints on the analysis procedure. For example, the choice of a 1 ms/bin channel advance rate for the multiscalar was based on an estimate of the accuracy with which an absolute arrival time could be assigned to each photon event. In this section this timing accuracy is considered.

The error in measuring the absolute photon arrival times consists of two components, a) a fixed delay, and b) a variable component (or jitter). A fixed time delay component merely introduces a constant phase shift to all of the events and therefore does not affect the present error analysis. The following factors contribute to the variable timing error.

1. The variable conversion time of the flight pulse height analyzer
2. The variable delay due to buffer storage and periodic data transmission rate

3. The errors experienced in recording the 80 kHz signal in synchronization to the WWV signal (including tape recorder speed fluctuations).

The variable delay in the PHA is due to the photon energy dependence of the pulse-height analysis time. The conversion time of an event varies from $\sim 5 \mu\text{s}$ for an event in channel 1 to $\sim 30 \mu\text{s}$ for an event requiring full scale conversion (256 channels). This is true for conversion on both the LER and HER ranges. This delay is much smaller than the other sources of timing error and was therefore neglected.

One of the two major sources of error is the variable delay between entrance of an event into the buffer and its transmission to ground. The minimum buffer delay occurs when an event is loaded into a completely empty buffer and is immediately read out upon reaching the last stage. This delay is approximately $15 \mu\text{s}$. The maximum delay of 1.1 ms occurs when the event fills the buffer and therefore is delayed four readout periods ($4 \times 280 \mu\text{s/period} = 1.1 \text{ ms}$) before being transmitted to ground. Any delay between these minimum and maximum values is allowable. This variable delay gives a jitter in the arrival time of events. A measurement of the buffer time delay distribution is difficult, but if we assume the average to be the mean of the maximum and minimum values ($\sim 0.5 \text{ msec}$) we can assign a rough timing uncertainty of $\pm 0.5 \text{ ms}$ maximum to these buffer effects. The most probable error, however, is more likely to be $\pm (0.2 - 0.3) \text{ ms}$ because the buffer only becomes full a small percentage of the time.

The second important source of timing uncertainty which affects the assignment of an absolute arrival time to an event is the error in synchronization of the 80 kHz oscillator signal to the WWV signal. Due to fluctuations in WWV signal transmission and tape recorder speed fluctuations,

there is considerable jitter in the recording of the WWV seconds markers. When synchronizing the 80 kHz signal to these markers, short term phase fluctuations did occur, but efforts were made to hold them to $\lesssim 1.0$ ms at any given time. This process was hampered by the poor WWV signal which was recorded on some sections of the magnetic tape. On some sections of the tape the phase synchronism was in error by more than ± 1 ms. These sections were rejected for use in the data analysis.

It is important to realize that this synchronization uncertainty of ± 1 ms maximum is independent of the length of interval over which the synchronization process was carried out. It is a non-accumulative jitter type of effect. Thus the absolute phase error at the end of 10 seconds could be $\lesssim \pm 1$ ms, and at the end of 10,000 seconds it would still be $\lesssim \pm 1$ ms. Because of its non-accumulative nature, this synchronization scheme has poor short term stability (~ 1 part in 10^4 over a ten second interval) but very good long term stability (~ 1 part in 2×10^7 for the entire data integration time). It is this long term stability that is absolutely essential in the superposition method of analysis. When the recorded WWV signal was strong, synchronization could be maintained to an uncertainty of $\lesssim 0.5$ ms. This was the case for approximately 90% of the data interval. Otherwise, the error was $> \pm 0.5$ ms but always $< \pm 1.0$ ms.

By combining the above two sources of timing error, we find that the apparent time of arrival of a photon, as recorded on the magnetic tape, is measured with ± 0.7 ms resolution with an absolute maximum error of ± 2.1 ms (obtained by adding the worst case errors of each type).

An additional timing error which is important is the jitter in the phase alignment of the starting time of each

run to a precisely known WWV second marker. This jitter does not directly affect the assignment of an arrival time to each event on the tape and was therefore not included above. But it does introduce a timing uncertainty when the 32 runs are superposed to obtain the final phase plot. Its effect is to smear an otherwise sharp peak appearing in the data. A measure of this uncertainty was obtained by generating a test tape with a 2 ms wide simulated pulsar type signal, as shown in Figure F-1. A 1000-second portion of this data tape was then analyzed using the superposition technique in two ways, 1) one long 1000-second run was made at the exact simulated pulsar frequency, and 2) the data interval was subdivided into ten 100-sec long runs, and each run made at the exact simulated pulsar frequency and superposed, using the computer aligning program. The results of these analyses are shown in Figure F-1b and c. The subdivision into short runs with the resynchronization error at the start of each run has smeared the 2 ms wide peak into three or four channels giving it a Gaussian-like shape. From the results of several of these test runs, this particular type of timing uncertainty was estimated to be ± 0.5 ms maximum. When this effect is combined with the absolute arrival time error discussed above, we obtain a total time uncertainty of ± 0.9 ms.

The basic phase resolution of the multiscaling sweep process used in the present analysis is equal to the width of one channel. Because of the ± 0.9 ms absolute arrival time resolution, a 1 ms channel width seemed to provide sufficient phase resolution for the analysis and was therefore chosen as the basic channel width. In fact, since a ± 0.9 ms jitter would tend to smear a narrow peak ($\lesssim 1$ ms wide) into two or more channels, the final phase plots were obtained by adding adjacent channels in groups of two. This has the effect of

Figure F-1

Results of using the pulsar search technique on simulated pulsar test tape. (a) Parameters of the artificially generated pulsar signal: a 2 ms wide pulse with a signal-to-background ratio of $S/B \sim 0.05$. The signal was generated by gating in random pulses for 2 ms every 33.112300 ms, on top of a random background signal. (b) Phase diagram resulting from the pulsar analysis when one 1000-second multiscaler run of the data was used. (c) Phase diagram resulting from the pulsar analysis if data is divided into ten 100-second multiscaler runs. Smearing and lowering of the peak amplitude compared to (b) is due to errors involved in synchronizing the start of each multiscaler run to an exact second of absolute time.

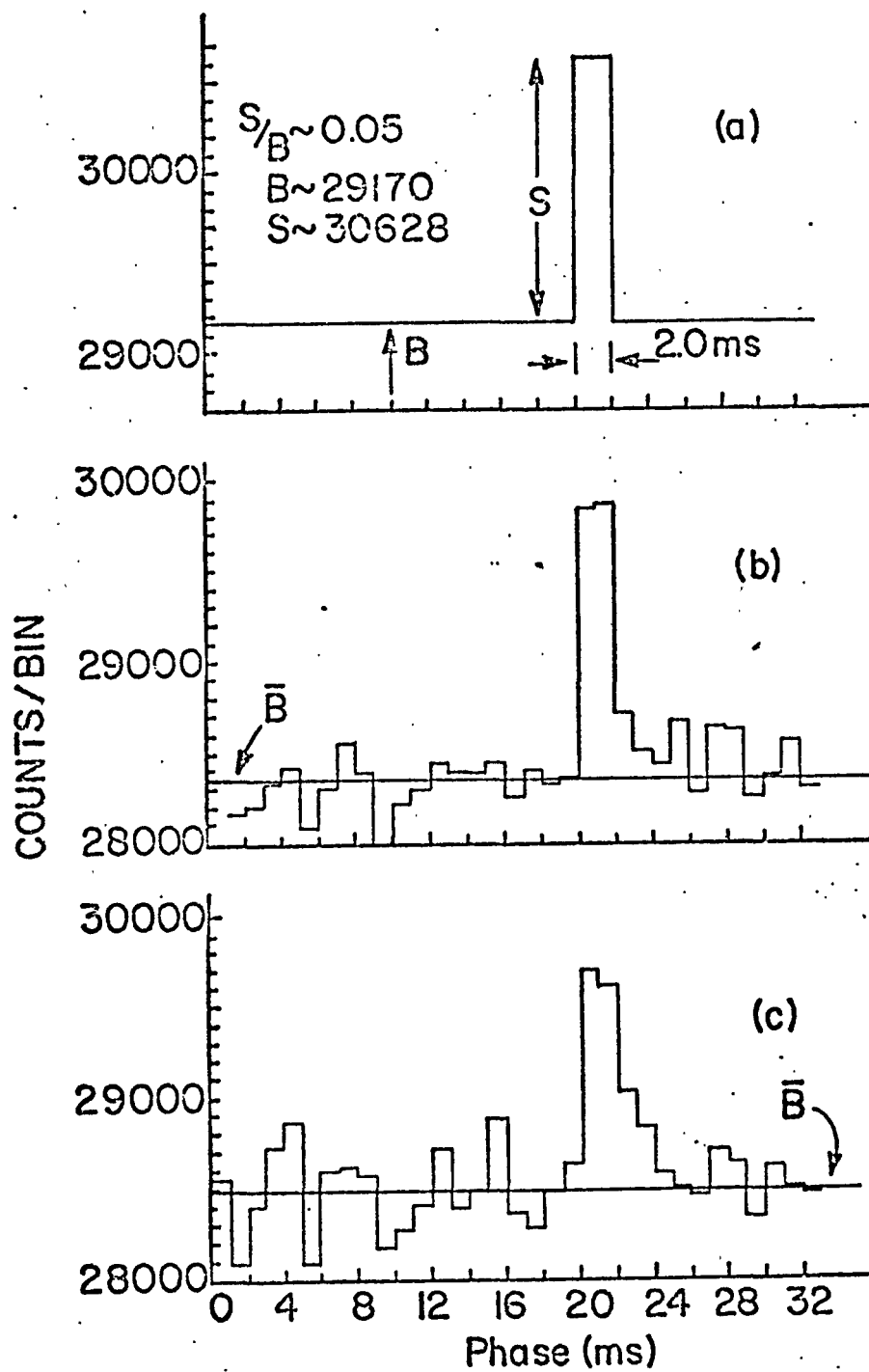


Figure F-1

improving the counting statistics per channel and increasing the chances of seeing a weak pulsar signal. However, this is achieved at the expense of losing detail in the information about the time profile of the pulsed signal.

In summary, we can say that in order to optimize the pulsar search, the period synchronization must be maintained to a stability of 2 ns/period or better (7 parts in 10^8) over the complete data interval. Also, the ± 0.9 ms uncertainty in the knowledge of the absolute arrival time of photon events indicates that we can expect to obtain only crude pulse shape structure from the final phase diagrams.

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