A Personal Perspective on the Early Years of High Energy Astronomy: from Minnesota to San Diego

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"History will treat me kindly for I intend to write it"
-Churchill

I. INTRODUCTION

The objective of this paper is to present a history of my early research and its contributions to the origin and development of High Energy Astronomy.

I became interested in the possibility of detectable cosmic X- and γ-rays as a graduate student during the late 1950's while doing cosmic ray research under John Winckler at the University of Minnesota. We made a number of discoveries of hard X-rays produced during aurora displays and solar flares. Winckler suggested I investigate the possibility of similar emissions occurring beyond the Solar system. This lead to the realization that stars, galaxies, and even objects in the extragalactic sky may be emitting detectable X-rays or γ-rays. Radio astronomy was then opening a whole new view of the Universe; it seemed likely the same was possible in the light of high energy radiations. Others had also speculated on the idea of a Gamma-ray Astronomy, it seemed the observational possibilities were unlimited. I began to investigate the promise of high energy astronomy not knowing this was to become the focus of my professional life.

It soon became clear that a better understanding of the radiation background at balloon and satellite altitudes, as well as new detector technologies were needed to obtain the improvements in sensitivity required to detect the weak fluxes expected. After initiating these studies, I developed an exploratory experiment for the first Orbiting Solar Observatory, launched in March 1962,

Meanwhile, I had obtained a faculty track appointment at the University of California San Diego, where I continued the work started at Minnesota. I initiated the High Energy Astronomy Group at UCSD almost concurrent with the discovery of cosmic X-ray sources on a rocket flight in 1962. The scope of the research encompassed not only the expanding area of X-ray astronomy, but also studies of the active Sun and the search for discrete γ-ray lines from nuclear process in astrophysical settings. Discoveries in new research areas often depend on technical advances. Developing high sensitivity, low background X-and γ ray detectors also required understanding the physics of cosmic-ray produced secondary radiations.

This research was conducted over a period of 50 years and required contributions from a large group of scientists, students and technical support personnel. However, this paper will focus primarily on the first decade. As the founder and faculty leader of the group, my work is inextricable from that of the collective. I chose to write in the first person from my recollections and hope that the work of my colleagues is correctly represented. I apologize if, at times, this is not the case.

II. THE ORIGIN AT MINNESOTA

A - Discoveries during the International Geophysical Year

I received my undergraduate degree in Electrical Engineering from the University of Minnesota in 1954. During this period, I worked part-time in the Physics Department's Electronic Shop, constructing and designing equipment for the various research activities. After working on electron physics problems relevant to vacuum tube technologies for a Masters degree in Engineering, I switched to graduate work in Physics. In 1956, I joined the Minnesota Cosmic Ray group under the direction of Ed Ney and John Winckler, who became my PhD advisor. My thesis project was to determine the spectrum of cosmic ray Alpha particles involving a balloon-borne instrument flown near the Geomagnetic Equator. I obtained my PhD in 1960. However, much of my graduate student time was devoted to one of Winckler's projects studying time variations of Cosmic rays and related geophysical effects during the International Geophysical Year (IGY), 1957–1958.

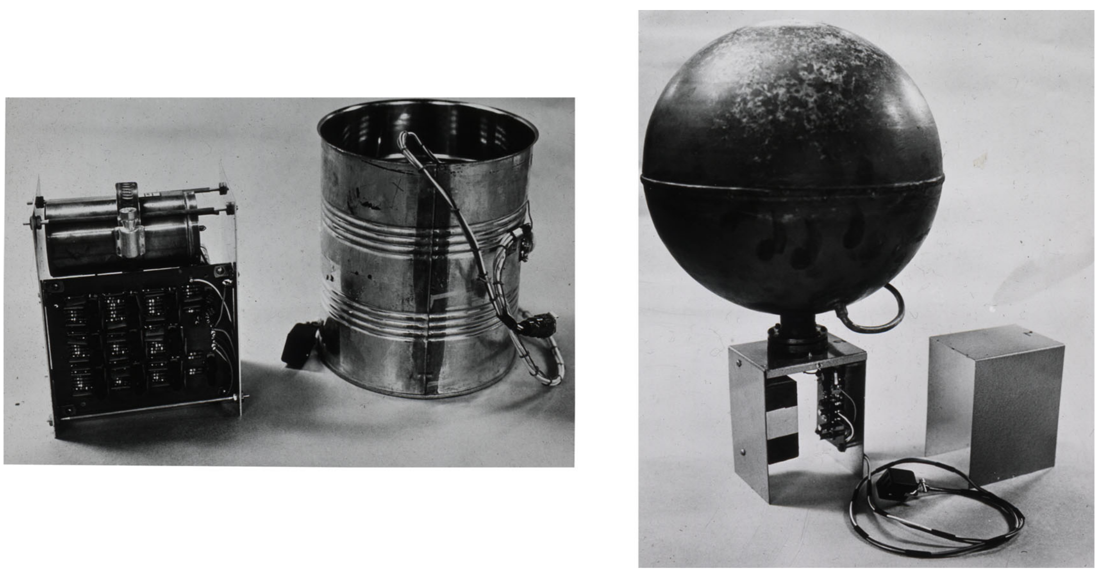

Fig. 1 – The Cosmic ray Geiger counter and ion chamber used on the IGY balloon flights. The instruments were in a foam thermal container during flights.

The concept was to utilize a simple apparatus: a cosmic ray ion chamber and Geiger counter, shown in figure 1, on a high altitude balloon system which could be quickly launched, even from remote sites, in response to Solar or geophysical events, such as Solar flares and magnetic storms (Peterson et al.1958). In addition to the ion chamber and Geiger counter, the balloon carried a low frequency radio tracking beacon and cut-down timer, a down-pointing camera giving daytime trajectory information from terrain photos and also recording the data, and a telemetry system giving line-of-sight real-time data recovery. The various flight components were tied in a chain with a nylon cord and electrical connecting cable to form a “flight train”. The 60 lb load could be hand-launched on an 180,000 cu ft. (5,000 cu meters) helium filled polyethylene balloon, which carried the instruments to an altitude of about 100,000 ft (35 km). Some 80 flights were launched during the IGY maintaining instruments at high altitudes for about 900 hours during the 1.5 yr period.

Two important discoveries relevant to my future work were made during the IGY project. The first was the discovery during the inaugural IGY flight from Minneapolis on the night of 30 June/1 July 1957, of ionizing radiations associated with a visible aurora fluctuating overhead. Since it seemed unlikely that the counting rate increases over background were due to direct particle effects, bombardment by hard X-rays was a real possibility (Winckler and Peterson, 1957). Energetic electrons accelerated in the far reaches of the Earth magnetic field follow the field lines and are stopped at several hundred kilometers altitude in the ionosphere. These electrons excite oxygen and nitrogen atoms producing the visible aurora. In addition, if the precipitating electrons are sufficiently energetic, they produce hard X-rays through the bremsstrahlung process. Such X-rays have a much longer range in the upper atmosphere than the electrons, and can penetrate to balloon altitude at 35 km. The discovery of the trapped radiation (the Van Allen belts) in 1958 identified a reservoir of particles that could be precipitated into the atmosphere by disturbances in the Earth’s magnetic field. A succession of space missions following this discovery elucidated the magnetosphere, as well as the acceleration and transport of energetic particles to produce the aurora during magnetic field disturbances.

The second discovery was an 18 second burst of radiation during a Class II Solar flare that occurred during an IGY balloon flight from Guantanamo Bay, Cuba on 20 March 1958, as shown in figure 2 (Peterson and Winckler, 1959). Once again, direct particle effects at the low magnetic latitude of Cuba were unlikely. The ion chamber/Geiger counter ratio indicated that the origin was due to hard X-rays or γ -rays. This event was the first detection of extra-terrestrial hard X-rays or lower energy γ -rays. After collecting other simultaneous radio and optical observations, we determined the explanation was the presence of electrons accelerated in the magnetic field region during the flare. The radio emission was produced by the synchrotron effect and the X-rays by bremsstrahlung of the same population of electrons in the solar atmosphere or precipitating into the photosphere.

It is interesting to note that this first detection of extra-terrestrial hard X- or γ-rays occurred in the same week as the publication of Phil Morrison’s paper “On Gamma-ray Astronomy” speculating on possible detection of such emissions. But neither Morrison nor us considered the possibility of cosmic fluxes in lower energy ranges where the discoveries occurred which opened the era of X-ray astronomy!

Winckler followed through these unexpected discoveries of X and γ–rays by incorporating a NaI scintillation counter into the IGY balloon flight train. Praful Bhavsar, a Postdoctoral Scholar from the Physical Research Laboratory, Ahmedabad, India, working on the IGY project led the development effort. This detector was used on a number of flights and made additional measurements of auroral X-rays and solar hard X-ray bursts (Winckler, 1963). We also considered the possibility that celestial objects may produce weak X-ray fluxes. In parallel, with

John's encouragement, I implemented a series of laboratory and balloon tests to study the behavior and background properties of various NaI detector configurations.

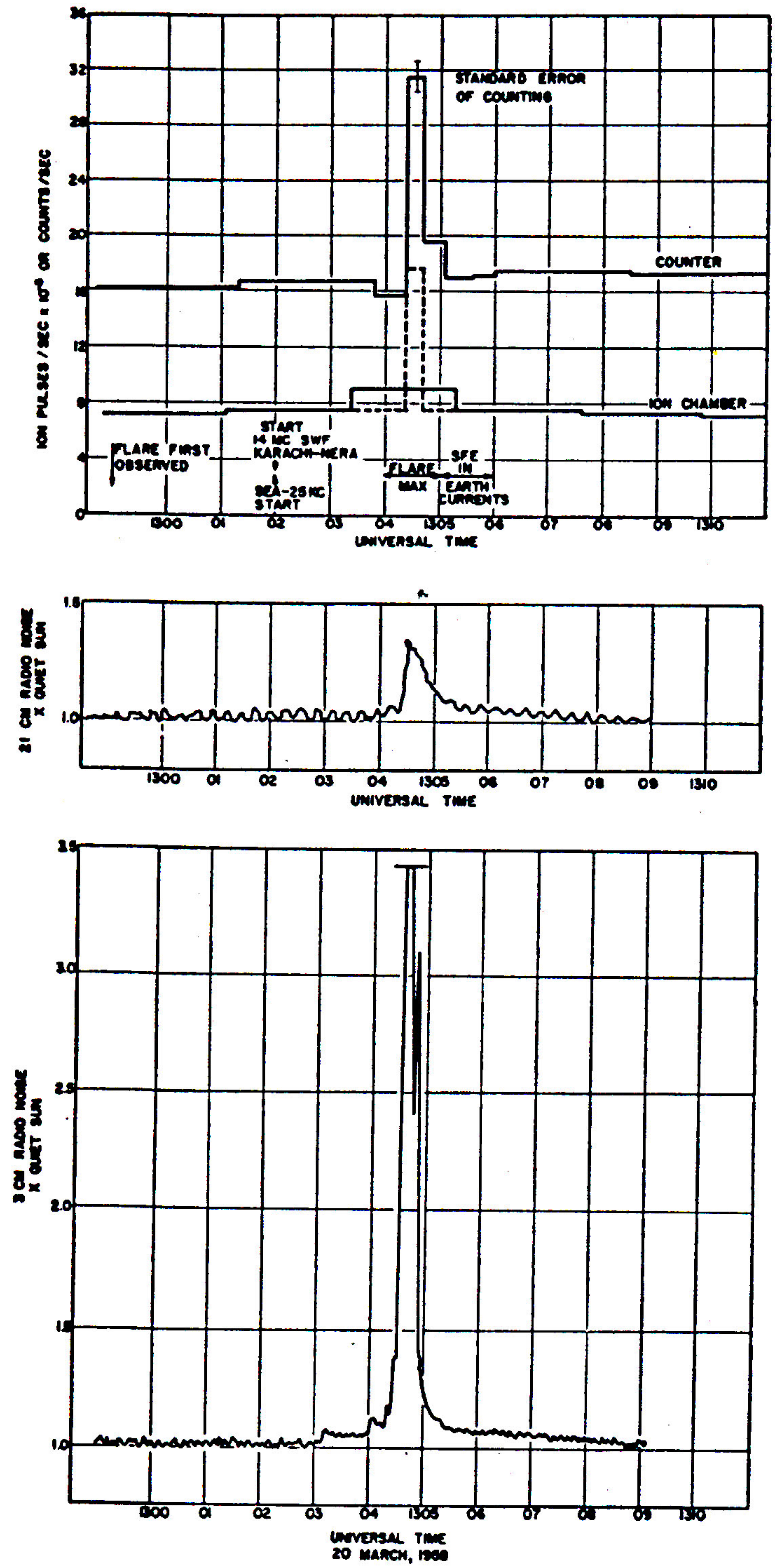

Fig. 2 – The burst of hard X-rays observed coincident with the class II solar flare on 20 March 1958.

B **- The Detection of Cosmic Photons**

For the reader not familiar with the methodologies involved, I describe the experimental techniques in the next paragraphs. The detection of cosmic X- or γ-rays (photons) requires that the photons, electrically neutral, interact and produce an electronic signal. Lens and mirrors generally do not work at these short wavelengths, although grazing incidence techniques can be used for soft X-rays. This technology has been highly developed and applied with great success on the Einstein (1978) and Chandra (1999) Observatories. At higher energies, mechanical collimation is used to define an instrument aperture.

Photons in the keV to MeV energy range have three basic interactions with matter: first, an X-ray can interact with an atom ejecting a photoelectron; second, a γ-ray may scatter on an electron, reducing its energy (Compton scattering); third, if the energy of the photon is greater than several MeV, the γ-ray may create an energetic positron-electron pair. Any of these processes produces energetic electrons in matter; which one dominates depends on the X- or γ-ray energy and the material. Energetic electrons, or any charged particles, passing through matter collide with the atoms leaving a path of electron-ion pairs. These electrons and ions are basic to forming the electronic signature of an ionizing event; the exact method depends on the device and the application as in some examples given below.

An ionization chamber is filled with an inert gas, ion-electron pairs are collected and the electric charge or current is measured. A Geiger counter is filled with gas at high pressure so the energetic electron initiates a discharge and the event is simply counted. Therefore, an ion chamber only measures the radiation dosage passing the walls and interacting in the gas; a Geiger counter detects an interaction. Neither provides much detail on the nature of the radiation. The thin window proportional counter, another gas-based device, has been a most important instrument in the exploration and discovery of the X-ray sky. The combination of gas, electrodes and voltage is such that each initial ion pair produced by the X-ray results in a cascade of additional ion pairs, multiplying the charge collected by thousands of times. This charge is proportional to the energy of initial X-ray. The thin counter window allows low energy X-rays, a few keV or less, to pass into the counter.

A charged particle losing energy in a NaI (Tl) crystal leaves the atoms in excited states, which decay giving a light flash or "scintillation". This is proportional to the energy loss and can be measured with sensitive photoelectric detectors, assuming the crystal is transparent to light. Certain organic liquids or plastics also scintillate when excited molecular states decay. The decay time, typically in the microsecond range, depends on the scintillation material and the doping agent. Scintillating materials with different properties and decay times can be optically coupled and viewed by a single phototube. Such an assembly, called a "phoswich", is extremely useful since the site of the energetic interaction can be determined from the light decay time. Solid-state detectors, constructed of materials such as Germanium (Ge), produce electron-hole pairs rather than ion-electron pairs. The resulting current pulse can be measured with a sensitive low-noise amplifier. The application of these techniques to X- and γ–ray astronomy has been discussed extensively in the literature (Peterson, 1975).

C - The OSO-1

The launch of Sputnik-I on 4 October 1957, and the subsequent formation of NASA on 1 October 1958, opened new research opportunities in the area now known as Space Science. John Winckler, who had Washington connections, became involved in early Air Force space missions taken over by NASA. He proposed a ruggedized version of the IGY ion chamber/Geiger counter package, which was accepted and flown on Explorer VI and Pioneer V. These instruments provided new information on the extent and nature of the trapped radiation, and formed the basis for the PhD work of my colleagues on the IGY project, Roger Arnoldy and Bob Hoffman.

While working on the Explorer and Pioneer projects, Winckler met John C. Lindsay who had formed a solar physics group at the newly established Goddard Space Flight Center (GSFC). Lindsay, working with NASA Headquarters, was leading the development of a satellite called the "Orbiting Solar Observatory" (OSO) to study solar radiations. It was expected this would evolve into a series, much like others in the developing lineup of NASA space missions. Winckler and Lindsay were of like minds, and the idea evolved to include X-ray and γ-ray experiments on the first OSO. Based on my earlier studies of NaI detector configurations and their background, we decided on an instrument configuration consistent with the objectives of observing hard X-ray events from the Sun and possibly producing a sky map if strong sources were present. We discussed various detector possibilities based on scintillation counters and wrote a simple proposal for the OSO.

In early January 1960, I attended the first meeting in Boulder, Co, between the spacecraft designers and scientific groups interested by the OSO project, designated S-16. The spacecraft built by the Ball Brothers Research Corporation (BBRC), was based on technologies developed for rocket-borne solar pointing systems. There were two operational parts to the spacecraft: a section which pointed UV and soft X-ray instruments at the Sun with arc-minute stability, and a 30 RPM rotating wheel section, which provided an inertial platform for the pointed platform. The wheel also provided spacecraft services, and could accommodate additional scientific instruments. No experiments had yet been selected for the first OSO mission; the meeting was a bit of a "fishing expedition" to find instruments which could be made compatible with the proposed spacecraft design, and could likely be delivered in time for an estimated 18-month launch schedule. About a dozen experimenters were present. I do not know how the final selection of instruments for the S-16 was made; in the early days of NASA, there were few formal review processes. But shortly after, the go-ahead was given to develop a "Hard X-ray and Low Energy Gamma-ray Instrument" for the mission. Winckler and I became Co-PI's, and the funding started!

The instrument complement consisted of three components: a 50-150 keV NaI scintillation counter of 10 cm^2 area with a Pb collimator to give a 22° aperture; a 5 cm dia. x 5.5 cm long isotropic NaI counter with a plastic anticoincidence (a phoswich configuration); and a third NaI counter arranged to form a rudimentary Compton telescope with the isotropic counter (Peterson and Howard, 1961). A small team of engineers and technicians headed by R.L. (Bob) Howard was assembled to work with me to design, construct and test the instrument. The prototype instrument was delivered early 1961, after a difficult development period. We then built a much improved flight unit, which was launched from Cape Canaveral on the First Orbiting Solar Observatory (OSO-I) on 7 March 1962, into a nearly circular 575 Km orbit.

The completed instrument is shown in figure 3. The electronic circuit boards were placed in modular sections, which also supported the detectors. OSO-1 is shown in figure 4. The instrument was located in one of the wheel compartments of the OSO spacecraft, looking radially outward. The mission produced data for about three months, after which various spacecraft systems, including the on-board tape recorders, failed.

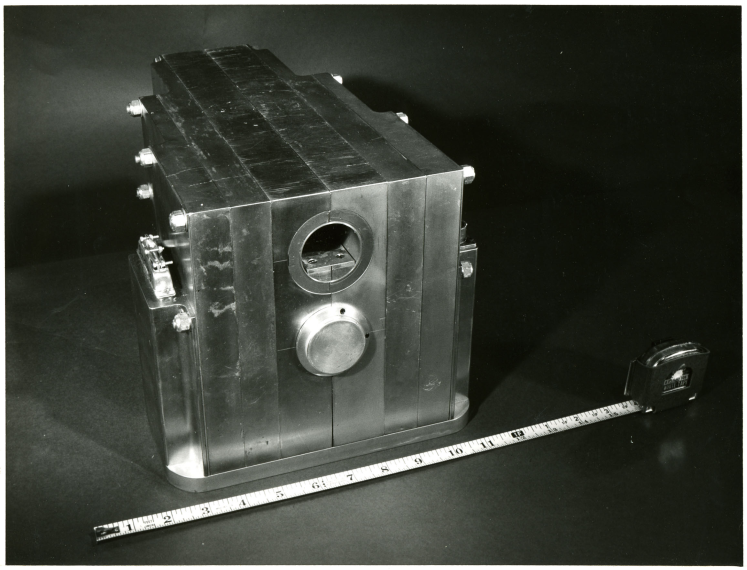

Fig. 3 – The University of Minnesota Gamma-ray experiment for the OSO-1.

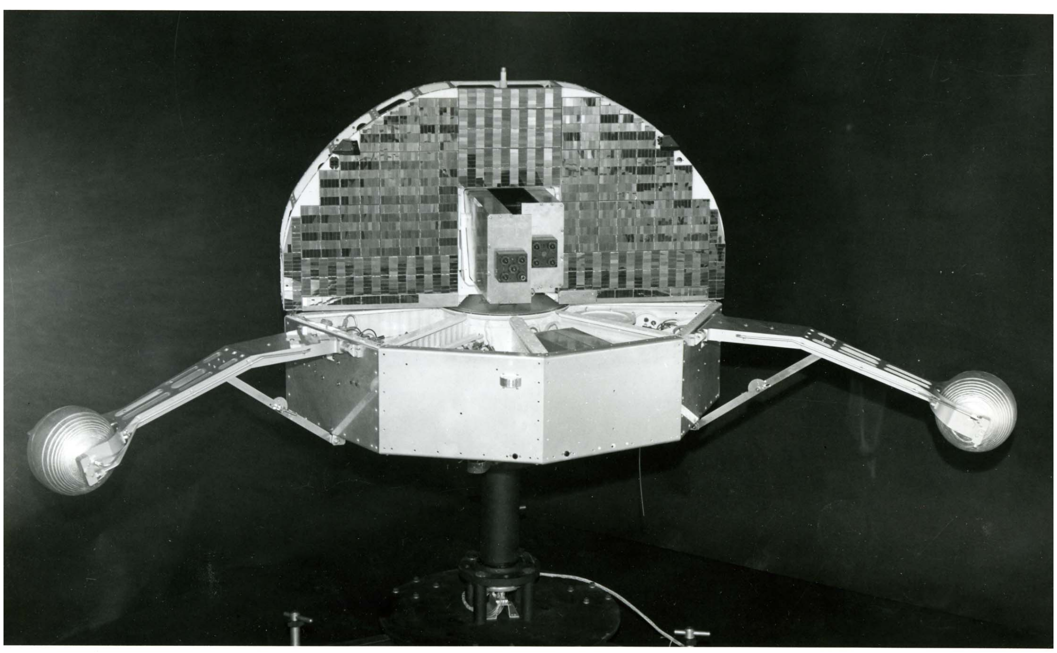

Fig. 4 – The OSO-1 spacecraft. The UofM instrument was located in the rotating wheel structure pointing radially outward.

Since the wheel plane was constrained to within a few degrees of the Earth-Sun line, the Sun, the sky, and a portion of the Earth below were scanned with each nominal 2-sec. rotation. Data was accumulated in 16-22.5 degree bins referenced to the Sun angle. Accumulated counts were transferred to six binary registers and read in a quasi-digital format to an analog subcarrier channel. Diagnostic information was read to the analog channel during the spacecraft night portion of the orbit, as no sun-synchronization was available. The low information rate permitted strip chart recordings to be read directly for test and verification purposes.

The OSO-1 telemetry was based on an FM/FM system with a subcarrier assigned to each instrument. Data accumulated on an on-board tape recorder for the 90 min. orbital period, and was played back during the passage over the NASA tracking station network near the 75˚W meridian in Central and South America. Station tapes were sent to GSFC where each subcarrier channel was stripped out and sent to the experimenter. A system was constructed at Minnesota that de-commutated the data and produced punched cards for analysis in a mainframe computer. This system never worked reliably despite extensive efforts. Because of this, the early orbital data tapes were played into strip charts, like the verification data. It required a week of work by a part-time undergraduate student to read and analyze data from each orbit. Meanwhile, unread tapes of some 100 orbits had accumulated!

During the development of the OSO-1 instrument, I continued the detector studies and implemented a series of balloon flights testing various counter, shielding and collimation methods. It soon became apparent that the shielding and background reduction problems were much more complex than earlier perceived, and that the OSO-1 instrument was not likely to obtain its objectives. Lead shields actually produced more background than they attenuated, resulting in various anticoincidence techniques being only partially successful. It occurred to me that an active attenuating shield of dense scintillating material in an anti-coincidence mode would solve some of these problems; however purchasing the material and constructing such a shield for testing seemed then completely beyond the laboratory resources at Minnesota.

During a meeting with Lindsay at GSFC, I found that a member of his group, Kenneth Frost, was already developing a NaI counter with an active CsI (Tl) collimating shield for the second OSO. After a discussion of problems in implementing such a device, Ken and I formed a collaboration to do a balloon test of the proposed configuration. The test flight was flown from Minneapolis in the summer of 1962. Besides obtaining limits on hard X-ray emissions from the quiet Sun, extensive data on atmospheric γ-rays, instrumental background, phosphorescence decay effects, and anti-coincidence requirements were obtained (Frost et al. 1966). Knowledge from that experiment was incorporated into later GSFC and UCSD instrument designs.

The spring and early summer of 1962 was an exceedingly hectic time for me. Data from the OSO-1 were accumulating in boxes, and the integration and ground test of the Ken Frost detector system presented more problems than anticipated. The first balloon flight failed at launch so a second flight had to be scheduled, which was successful. It was also an emotional time with the preparation for my departure to San Diego: saying good-bye to family, friends and colleagues, as well as packing home and office for the move late July to the Promised Land of Southern California!

III. UNIVERSITY OF CALIFORNIA SAN DIEGO

A – High Energy Group Beginnings

My family and I arrived in San Diego early August 1962 after a restful 10-day camping trip across the Western states. I officially joined the Physics Department at the beginning of the academic year in September.

UCSD was formed from the Scripps Institute of Oceanography (SIO) through the efforts of senior scientists, particularly Roger Revelle, and chartered as a regular campus of the University of California 18 Nov 1960. The early 1960's were a period of great expansion at UCSD. The first building phase on the new campus was nearing completion. New Academic Departments were rapidly being established. The present site of UCSD on a mesa overlooking the Pacific was under construction at that time, so I was temporarily located in Sverdrup Hall at SIO. Carl McIlwain, a co-discoverer of the earth's trapped radiation, (Van Allen belts), and developer of the B, L coordinate system, had also recently arrived. It was anticipated Carl and I would initiate Space Physics research within the growing Physics Department. I had transferred some experimental equipment from Minnesota, and was creating a group focused on X-ray astronomy. My office and laboratories were moved to the brand new Physics building (presently Mayer Hall) in the summer of 1964. The first freshman class of undergraduates was admitted for Fall Quarter 1964. The Physics faculty now numbered about 20. Margaret and Geoff Burbidge were leading the Astrophysics faculty and I, among others, was a junior member. Areas of astrophysical research included extragalactic and X-ray astronomy, theoretical astrophysics, and space physics. Visiting scientific and postdoctoral fellows arrived, and a graduate student body was developing in space physics.

The faculty also decided that expanding into the evolving area of infrared astronomy would complement the Astrophysics activity. This was initiated in 1965, when Fred Gillett and Wayne Stein, two of Ed Ney's students, came from Minnesota. I had a discussion with Dr. Nancy Roman, Chief of Astronomy at NASA, about support for a potential IR group at UCSD and she was encouraging. An addendum to my NASA SR&T grant funded the IR program for the early years. Margaret and Geoff negotiated UC support for the Minnesota IR telescope on Mt Lemmon, Arizona that became a joint-use facility.

B - High Energy Astronomy Group Expansion

Back in 1961, I had made contacts with Dr. John Naugle, Program Officer in Space Sciences at NASA Headquarters, and Dr. Roman indicating my plans to move to San Diego and initiate a research program there. While still at Minnesota, I submitted a proposal through UCSD to NASA with the following objectives: 1) reduction and analysis of the data from the UofM experiment on OSO-1, 2) initiate a balloon program focused on the development of detector technologies, understanding background effects, and possibly observing cosmic X- and γ-rays, and 3) to develop a hard X-ray telescope for the proposed third mission in the OSO series. The proposal was accepted, but funded in three parts from different NASA funding sources. The central grant from the NASA Supporting Research and Technology (SR&T) program was for \$85,000/year, and ran through many modifications and extensions for twenty years. UCSD had also provided me with \$50,000 of start-up funds used primarily for equipment purchases.

The SR&T balloon project had three directions: observations of hard X-rays and low-energy γ-rays from astrophysical sources, understanding the physics of cosmic-ray produced γ-rays and instrumental backgrounds, and developing new instrumental concepts. Support for technical and programming staff was included in the proposal, as well as for undergraduate lab assistants and graduate students. These would gain hands-on experience with balloon instruments and data analysis techniques, and participate in the design and test phases of space missions. PhD thesis investigations could be based on data obtained from either a balloon flight series or from space missions. I also included the possibility of Postdoctoral Scholars and part-time undergraduate students working toward Bachelor degrees. In this writing, "student" will mostly refer to a graduate student working toward a PhD.

Almost simultaneously with the initiation of the UCSD program, two landmark discoveries were made, confirming my research effort was on a valid intellectual foundation. The first was the discovery by Giacconi and his colleagues at American Science and Engineering (ASE) on a June 1962 rocket flight of a strong soft X-ray emitting source in the direction of the Constellation Scorpius (Giacconi et al.1962). Furthermore, the entire sky seemed to glow in X-rays, a more or less uniform background likely of a very distant origin in the Universe. The second discovery was by Jim Arnold at UCSD and his collaborators at the Jet Propulsion Laboratory (JPL) using the Lunar probe Ranger-3. This mission carried a simple isotropic NaI scintillation counter mounted on a boom designed to measure the spectrum of γ–rays emitting from the moon to determine the chemical composition of the lunar surface. During trans-lunar orbit, however, the detector measured unexpectedly high counting rates in the 0.3-3 MeV range, which was interpreted as due to a more-or-less isotropic emission of gamma-rays from cosmic distances (Metzger et al.1964). Jim Arnold and I later collaborated on a number of programs and missions, including a major instrument in lunar γ-ray spectroscopy as part of the Apollo program.

C – Initiation of the Balloon Program

Developing a capability to build and fly instruments on high altitude balloons became a priority upon my arrival at UCSD. Discoveries were rapidly being made in cosmic X-rays, observations of these same sources in the higher energy range accessible to balloons seemed a next logical and eminently feasible step. Furthermore, continuing the detector development activity required access to the full cosmic ray environment for verification and test. To accomplish these objectives, I needed scientific balloon launch and operational services.

In the late 1950's, General Dynamics Astronautics (GD/A) in San Diego had established a Scientific Research Laboratory. Among other groups in the lab, James (Jim) Vette created a balloon flight facility and made early discoveries of solar flare X-rays. Jim and I were in contact and later collaborated on space experiments. By the early 1960's, the ability of GD/A to support basic research was disappearing due to financial difficulties. Jim left GD/A and suggested I could acquire some of the personnel and equipment for the UCSD program. By the spring of 1963, two such personnel, Rod Jerde and Paul Brissenden, came to UCSD and formed the original technical team. GD/A also provided for balloon launch support during the summer of 1963. About five flights to study atmospheric γ-rays and background effects on the OSO-1 detectors were flown from an abandoned military airstrip near Dateland, Arizona. When the GD/A balloon group closed in late 1963, some of the equipment, including about five surplus military vehicles, was transferred to UCSD. This became known as "The Great While Fleet", example shown figure 5, and was used for several years to transport equipment to remote launch sites and to setup mobile telemetry receiving stations.

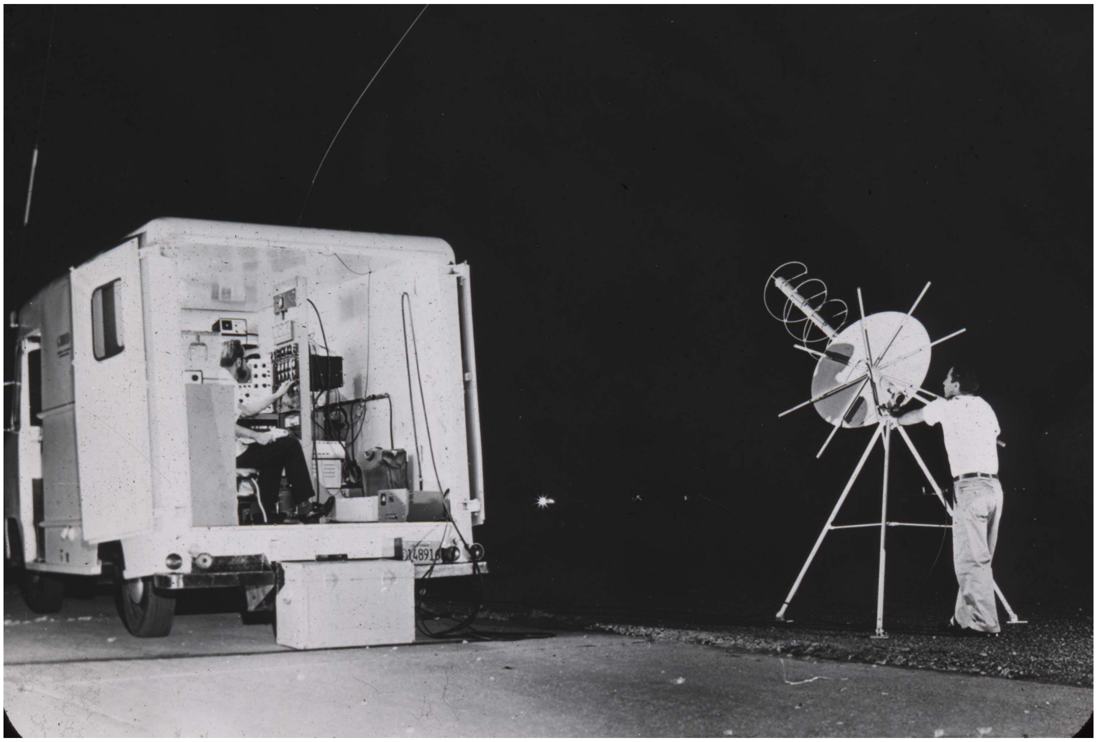

Fig. 5 – The telemetry van from the “Great White Fleet” used on many of the early UCSD balloon flights from Dateland, Arizona and Palestine, Texas.

Meanwhile, the National Science foundation had established a facility for scientific ballooning based in Palestine, Texas, to be administred by National Center for Atmospheric Research (NCAR) in Boulder, Colorado. NCAR had agreed to provide operational support for NASA projects requiring balloon flights. The first Palestine flights for UCSD were flown in 1965, and a high level of activity, up to five flights/yr, was maintained until the mid 1970's. The NCAR facility, which later became the National Scientific Balloon Facility (NSBF) under NASA management, had several launch locations worldwide used by UCSD. Despite fewer flights in recent years due to increased complexity of balloon experiments, about 80 flights carrying instruments originated at UCSD had been flown by the year 2000.

D - OSO-1 Data Analysis

The primary data set from OSO-1 was partially reduced at the UofM using the punch card system described earlier. Despite the awkwardness and unreliability of that system, reduction continued, and the undergraduate who programmed the analysis software at Minnesota came to UCSD for a brief time to install it on the UCSD computers. It was evident however, a better reduction method was needed, and Paul Brissenden constructed a new system. Analog magnetic tapes were converted to computer-compatible magnetic tapes with a digital sampling system. De-commutation was accomplished with a program designed by Louis Huszar, a graduate from the University of Illinois, who was leading our software developments. After the OSO-1 data run, this system, with many variants, was used extensively in the reduction of data from other spacecraft and balloon experiments.

Using results from early analysis, Tom Delmer, a graduate student at UCSD, discovered that passage of the spacecraft through the geomagnetic trapped proton regions produced the radioactive isotope I^{128} with a 28 min. half-life in the NaI counter crystal (Peterson, 1965). Someone pointed out "this is the hard way to do nuclear physics"! Predicting background induced by cosmic rays and trapped radiation in instruments soon became a "Cottage Industry".

Most of the X- and γ-ray events in the OSO-1 data were due to background. In order to understand these effects, the OSO-1 spare instrument was flown on a series of diagnostic balloon flights from Dateland in two configurations. The first was the complete instrument with a modified data system. The second had the structure and electronic boards removed, and the almost bare detectors fixed in a Styrofoam block well removed from other mass of the balloon system. In the latter, counting rates were remarkably lower, indicating most of the counts in the OSO-1 instrument were produced in the local mass of the instrument, the spacecraft, and even in the lead collimating shield. I decided success in X-ray astronomy depended on "leaving the lead on the ground"!

Despite this, several detections of hard X-rays during solar flares demonstrated an association with concurrent microwave bursts (Winckler, 1963). Limits of fluxes at higher energies were consistent with the Ranger-III detection of a possible diffuse cosmic γ-ray background (Peterson, 1966a). The results on cosmic rays, background production in the spacecraft and instrument, and related effects were published in a comprehensive UCSD technical report (Peterson, 1967b).

After the discovery by Ricardo Giacconi and his colleagues of cosmic X-ray sources in the 1-10 keV range in June 1962, one could speculate that such a discovery might have been made earlier by OSO-1 if the 50 keV threshold of its Pb collimated telescope had been set near the phototube noise limit of a few keV.

E – Participation in Advisory and Selection Committees

By 1964, I had been appointed to a sub-committee of NASA's Space Science Steering Committee. These committees, which met several times a year, were formed on a disciplinary basis to review scientific programs and proposals for missions as well as make experiment selections. The committees usually met at a NASA center or at an institution that had research programs relevant to the discipline associated with the sub-committee, allowing for contacts with scientific teams and laboratories. In the late 1960's, I was also invited to participate in the series of Woods Hole Summer Studies, which provided rational and direction for the overall scientific programs of NASA. For most of the reminder of my career, I had considerable involvement in the various advisory functions for NASA including both internal committees and external groups such as the Space Science Board. These meetings gave me considerable insight into the NASA structure and organization, "the NASA way of operating" and an introduction to the players involved both scientifically and administratively. This knowledge was extremely useful in developing the High Energy Astronomy Program at UCSD.

IV - ATMOSPHERIC GAMMA-RAYS AND COSMIC RAYS

A – Cosmic rays

Cosmic rays are the nuclei of atoms, stripped of all their orbiting electrons, accelerated to velocities approaching the speed of light and incident on the atmosphere. The acceleration to relativistic energies occurs in the interstellar medium likely associated with turbulent gas clouds formed from supernova explosions. The intensity of primary cosmic rays at the top of the atmosphere is about one per cm^2/second and depends strongly on the latitude because charged particles are deflected by the Earth magnetic field. Primary cosmic rays are mostly protons (hydrogen nuclei); about 20% are alpha particles (helium nuclei) and there are some heavier nuclei. Relativistic cosmic rays can have energies much greater than the rest mass energy of a proton, 1 GeV. This is thousands of times greater than the cosmic X- or γ-rays we are investigating. In the atmosphere, cosmic rays colliding with nuclei of oxygen and nitrogen atoms produce a bevy of secondary particles, which also interact and decay, producing the atmospheric γ-ray fluxes, and causing background effects in detectors. The cosmic ray flux at sea level, mostly due to mesons, is only a few percent of that reaching the earth.

Appreciating the transport of cosmic rays and γ-rays requires some understanding of the Earth atmosphere. Cosmic rays physicists think in term of atmospheric depth; that is the mass of the air column above a given height. At standard sea level, 76 cm Hg pressure and 20º C, the column depth is 1033 gm/cm^2, approximately equivalent to 10.33 m of water overhead. The atmospheric depth is exponential; for example: the depth at 15 km (49,200 ft) altitude is 121 gm/cm^2; at 30 km (98,400 ft), it is 12 gm/cm^2, etc. Relativistic cosmic ray protons have a range of about 70 gm/cm^2 in air before colliding with nitrogen and oxygen atoms to produce secondary cosmic rays. No primary cosmic rays reach sea level. Hard X-rays have a range of about 10 gm/cm^2, depending strongly on energy, hence the necessity of having balloon instruments flown at 40 km altitude. Soft X-rays in the 1-10 keV range have much shorter range and therefore observations are made from rockets or spacecraft hundreds of kilometers above the Earth.

B – Atmospheric Gamma-Rays

Understanding the production of secondary γ-rays by cosmic rays is essential to reducing their detrimental effects and therefore maximizing the sensitivity to relatively weak cosmic X- and γ-rays fluxes. A series of balloon flights using a 3” long by 3” dia. (7.5 x 7.5 cm) NaI counter with a plastic anticoincidence shield, as shown in figure 6, determined the total atmospheric fluxes up to about 10 MeV. This configuration had nearly an isotropic response and rejected events due to charged particles. These flights provided a reference for the intensity of cosmic ray produced γ-ray fluxes at various heights in the atmosphere.

Low energy atmospheric γ-rays originate from secondary electrons and from γ-rays having energies of hundreds of MeV. The high energy γ-rays produce electron-positron pairs; these pairs in turn also produce γ –rays, both components are losing energy as they cascade downward until the process stops in the lower MeV range. The remaining γ–rays multiple scatter to produce the spectrum measured over Palestine, Texas at 3.5 $gm/cm^{2,}$ 40º magnetic latitude, as shown in figure 7 (Peterson et al. 1973). The electrons and positrons are slowed by ionization loss; however, the positrons annihilate with ambient electrons to produce a 0.5 11MeV γ-ray line. I determined the intensity of this gamma-ray line in the atmosphere on a balloon flight over

Minneapolis, and verified its equilibrium with the secondary cosmic ray intensity (Peterson, 1963).

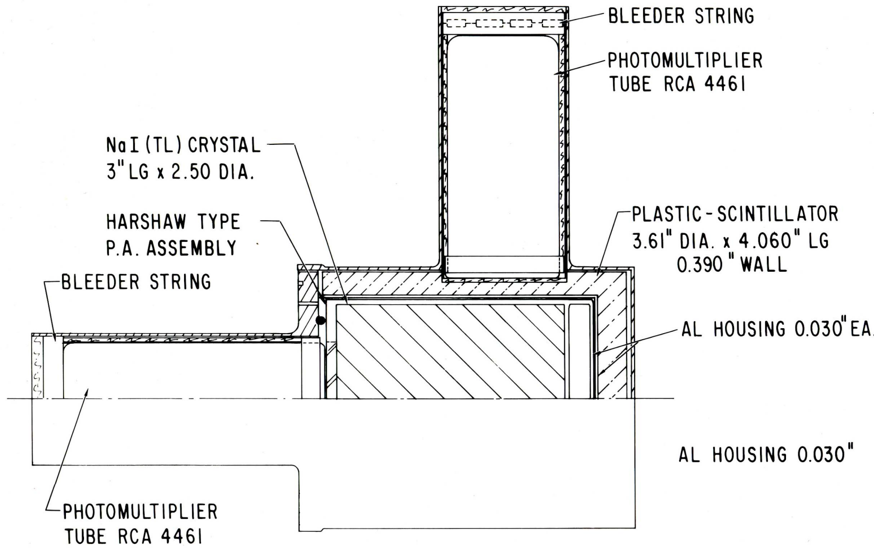

Figure 6 – The 0.3-10 MeV γ-ray detector with a nearly isotropic response. The plastic anticoincidence rejected charged particle effects.

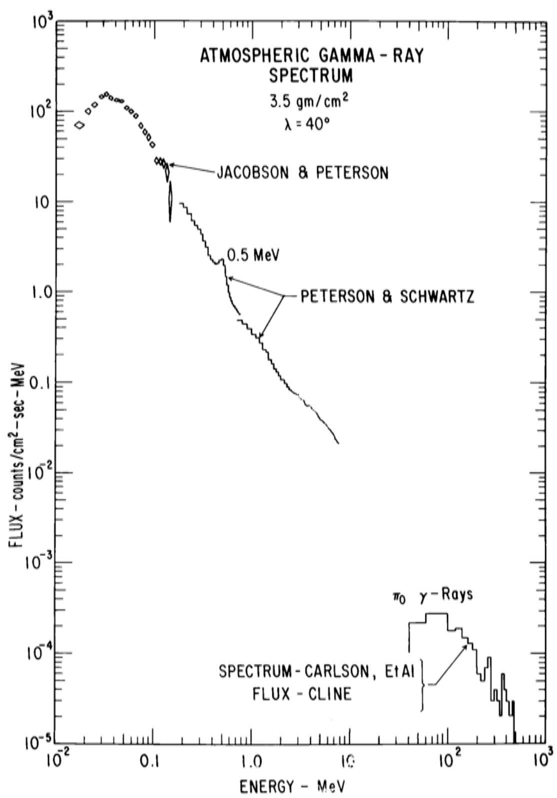

Figure 7 – The atmospheric gamma-ray spectra measured over Palestine, Texas with an isotropic counter. This flux originates at a much higher energies due to cosmic ray interactions.

This quasi-equilibrium of energetic secondary electrons and γ-rays above tens of MeV explain why a plastic anticoincidence shield around a heavy absorbing collimators is only partially effective in reducing detector backgrounds. While the direct particle effects are eliminated by the anti-coincidence, energetic γ-rays pass on, interact in the passive absorbing shield, producing a new set of background γ-rays, which can reach the detector. The active anti-coincidence absorbing collimator eliminates this effect.

The measured γ-ray background in any situation can be formulated in terms of radiation transport theory. Each material element exposed to cosmic radiation is a source of hard X-rays or γ-rays. If the "source function" is known for a given radiation in all matter surrounding a detector system, the background can be found by integrating over all the relevant source elements. Rather than estimating a source function due to cosmic rays from first principles, we used the flux data accumulated on many flights under different conditions to unfold the source function. We called this predictive calculation a "semi-empirical model" of γ-ray production. Dan Schwartz and Jim Ling contributed to this work and Jim Ling developed the model for his PhD thesis (Ling, 1975).

V - THE OSO-3

A - Development

The possibility, included in my initial proposal to NASA from UCSD, of developing an instrument for the third OSO (originally called S-57) to study hard solar and cosmic X-rays was accepted in early 1963. The basic instrument configuration, to be located in the rotating wheel of the OSO, was a Sodium Iodide (NaI) scintillation counter collimated by a Cesium iodine (CsI) cylinder in anti-coincidence to form a telescope. Since UCSD had no facilities to develop space hardware, we sub-contracted the development effort. The instrument group at BBRC (Ball Brothers Res. Corp.) was selected on a sole-source basis. I worked closely with their engineers to develop a preliminary design as well as schedule and cost. Since I had little prior experience in working with aerospace organizations, I greatly underestimated the cost in the initial proposal. Drs. Roman and Lindsay were most understanding and had a more realistic budget in their planning. In addition to the BBRC sub-contract, the final proposal to NASA for the S-57 project included support for Postdoctoral Scholars and graduate students, and verification balloon flights.

The detector design had a 9.4 cm^2, 0.5 cm thick NaI counter assembly inside the 2 cm thick cylindrical CsI (Na) collimating shield shown in figure 8 (Hicks, et al.1965). The X-ray energy spectrum was accumulated in eight logarithmically spaced channels over the 7-190 keV range. X-ray events, with timing and directional information, were read to the OSO tape recorder at a 12.5 bit/sec. rate. A preliminary version of the detector system flown to 105,000 ft (32 km) from Dateland, Arizona verified the concept.

The instrument for S-57 (later called OSO-C) was entirely constructed, tested and integrated into the spacecraft at BBRC. Don Hicks was the physicist in charge and Lou Reid led the electronic system design. Rod Jerde, several students, and I made many trips to Boulder during the design, construction and test of the instrument. Hugh Hudson, who earned his PhD from UC Berkeley, came to UCSD as a Postdoctoral Scholar in 1964, in anticipation of a flood of data on hard solar X-rays from S-57.

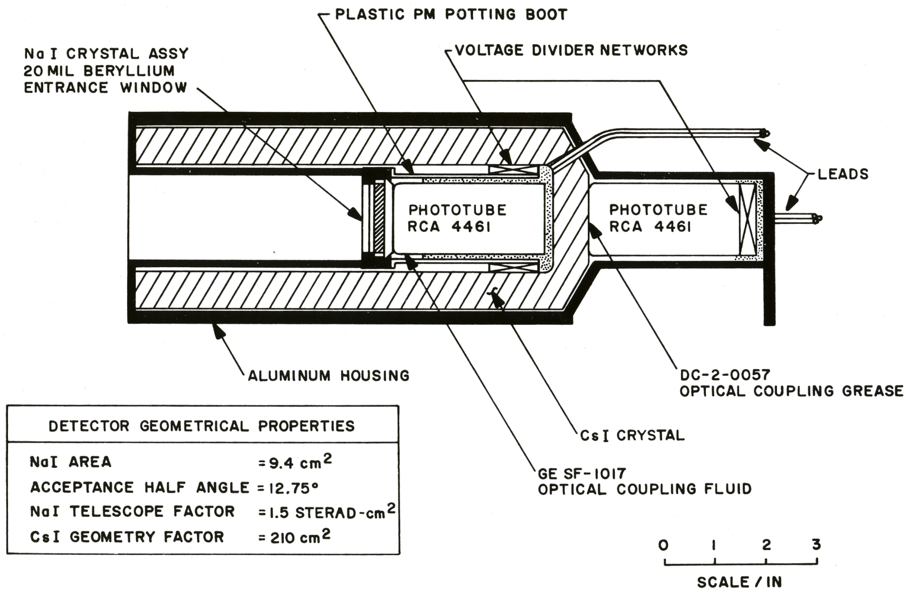

Figure 8 – The X-ray detector with an active collimator on OSO-3

Unfortunately, the launch of the S-57 on 25 August 1965 failed due to a malfunction of the third stage rocket and the spacecraft burned up upon re-entry into the South Atlantic. After this setback, the OSO series was re-scheduled and the mission rebuilt as OSO-E1, using mostly flight spare instruments. The replacement spacecraft was successfully launched on 8 March 1967, almost exactly five years after OSO-1, into a 550 km, 32° inclination nearly circular orbit. Renamed OSO-3, the instrument and spacecraft operated almost flawlessly for about 15 months at which time the tape recorders failed. Meanwhile OSO-2 had been launched in January 1965, carrying Ken Frost's instrument, the first hard X-ray telescope with an active CsI anticoincidence shield to be orbited. The OSO-2 also had its share of setbacks and tragedies; the story of the early OSO program, and some of the colorful personalities involved, has been published in a book by Alfred Bester (Bester, 1966).

B – Scientific Results

The UCSD 7-190 keV instrument was the only hard X-ray detector on OSO-3. Since the telescope was looking outward from the 30 RPM rotating wheel of the OSO, the 25.5° field-of-view scanned the Sun, the sky above the horizon, and the Earth below during each rotation. Since the wheel was constrained, like all OSO's, to a plane containing the Earth-Sun vector, the sky could be scanned every six months depending on the season and the wheel plane angle with respect to the ecliptic plane. Data was taken in a number of modes depending on day or night, differential or integral channels, etc. The design of the OSO-3 was frozen in September 1963, only nine months after the discovery of cosmic X-ray sources, too early to incorporate modifications taking this discovery into account. Hugh Hudson, along with the students Dan Schwartz, Mike Pelling and Dave McKenzie did most of the analysis on the OSO-3 data. A number of undergraduates also contributed to the data analysis.

Obtaining new results on time and spectral variability of hard X-ray events from the Sun was a prime objective of the UCSD experiment. The instrument collected data when the telescope field of view crossed the Sun, allowing a complete spectral measurement in the 7-190 keV range every 15 seconds. Since the initial discovery of hard X-ray emission associated with solar flares, there had been many such observations by NRL and on the Orbiting Geophysical Observatory. Various instruments on OSO's and other spacecraft had made observations in the EUV and low keV range; these emissions are usually associated with the dynamics of the multi million-degree solar corona.

The OSO-3 instrument was the first to determine the dynamic spectral changes of the X-rays above 7 keV. (Hudson et al. 1968). The sensitivity was such that no hard X-rays were observed from the quiet Sun, to a limit of 10^{-8} erg/cm^2-sec. Almost all flares and sub-flares with accompanying microwave bursts produce hard X-rays. Hundreds of bursts were observed, permitting statistical analysis of the events. The typical burst rise time was about 86 sec. and the decay time was 458 sec. The flux was typically non-thermal during the rise and thermal during the decay with effective temperatures often exceeding 50 million degrees. Few flares showed the very fast structure of the discovery event of 20 Mar 1958; those that did were invariably associated with an intense microwave burst. The major solar flares of 20 and 22 March 1967 produced enough flux to saturate the counters. More than 20,000 statistically significant bursts were detected in the 15 months of OSO-3 operation. (Hudson et al. 1969) The analysis of this data set became the PhD thesis of David McKenzie (McKenzie, 1972)

SCO X-1 was observed semi-continuously for a 30-day period in May and June 1967, extending the time scale of observations from a few minutes on rockets or few hours on UCSD balloon flights to many days. Simultaneous optical observations were obtained for several 10-day periods. This work showed that optical bursts lasting several minutes were also accompanied by X-ray bursts (Hudson, et al, 1970) and that the spectral shape of the X-ray bursts are the same as that of the non-flaring state. This implies the bursts are associated with a change in the volume, or the emission measure of the region producing X-rays rather than the temperature. The detailed analysis of the time structure of SCO X-1 X-rays and optical observations became the PhD thesis of Mike Pelling (Pelling, 1973).

Hugh Hudson, in collaboration with the students, also produced a series of papers on time and spectral signatures of a number of other identified cosmic X-ray sources whose spectra extended into the hard X-ray region. These sources included Nor X-2 and the extragalactic radio source Centaurus A, which was shown to be highly variable (Schwartz et al. 1972)

The spectra of the diffuse component of cosmic X-rays in the hard X-ray region was of interest to determine the mechanisms producing it, and to ascertain if this component was truly diffuse or the integrated effect of many sources. The study of this phenomenon was particularly difficult due to the varying background of the detector, to the irregular exposure to the sky, and to the contribution of known X-ray sources. The diffuse component, along with other measurements available by 1969, is shown in figure 9 (Schwartz et al.1970). The OSO-3 data points are the most precise of the many in the hard X-ray region. Dan Schwartz searched for anisotropies and set a limit of 5% to the maximum inhomogeneity in the sky, and 1% to a 24 hr component with respect to the celestial sphere. This requires at least 10^5 discrete sources in the sky at these energies. The explanation of the nature of the hard X-ray diffuse component is an unresolved issue at this writing; at soft X-ray energies, the diffuse flux is almost certainly due to the superposition of many point sources. In hard X-rays, it is also possibly due to the integrated emission of discrete sources, such as Active Galactic Nuclei (AGN's). Dan Schwartz based his PhD thesis on the spectra and isotropy of the diffuse X-ray sky (Schwartz and Peterson, 1974).

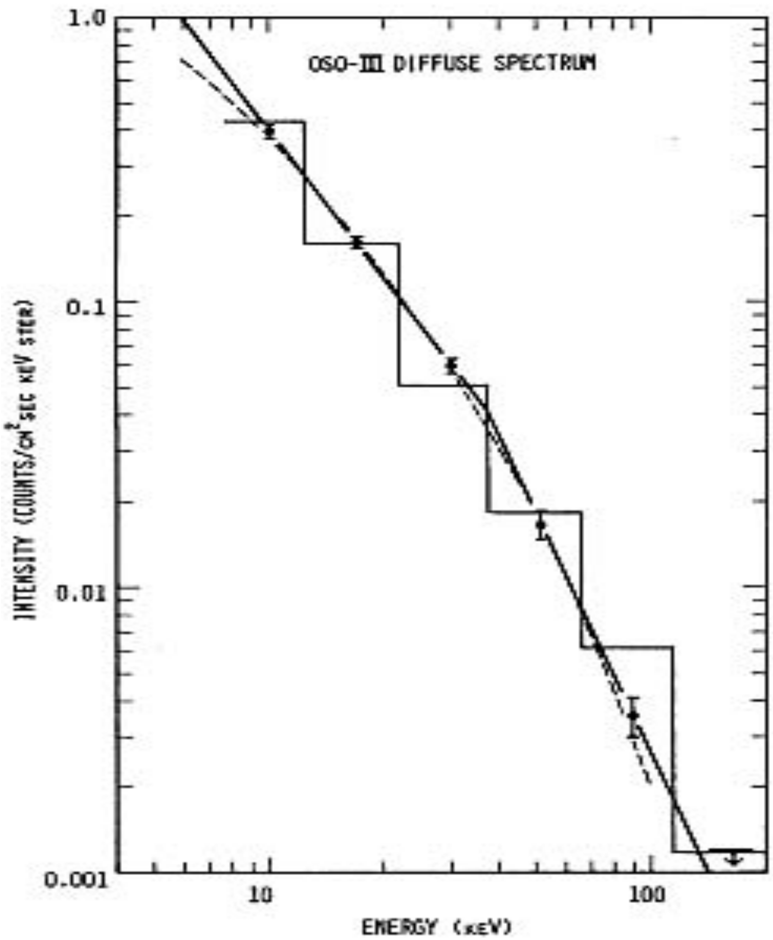

Figure 9 – The spectrum of the diffuse component of cosmic X-rays measured by OSO-3.

The OSO-3 also carried the MIT High Energy Gamma-Ray experiment of Kraushaar and Clark. This instrument discovered a flux of γ-rays in the 50 to 100 MeV region as a diffuse ridge on the celestial sky, coincident with the galactic plane. As discussed in an early review of the subject by Garmire and Kraushaar (1965), this flux was predicted as likely due to cosmic rays interacting with interstellar material in the higher density regions of the galaxy. This discovery defined the relevance of γ-ray astronomy to high energy astrophysics, and to our work at lower energies.

VI - DISCOVERIES FROM BALLOONS

A - Observations of Cosmic X-Ray Sources

By 1964 the new field of X-ray astronomy was rapidly expanding. In addition to the ASE/MIT consortium, other institutions with access to rockets had entered the field: NRL, Livermore Radiation Lab, and several European and Japanese groups (Giacconi and Gursky, 1965). Balloon investigations searching for hard X-ray and γ−ray sources were conducted by investigators at MIT, Rice University and CEN/Saclay in addition to UCSD. About a dozen discrete cosmic X-ray sources had been discovered; some of their properties, such as the spectrum, identification with radio or optical objects, and possible time variability were determined. After the launch of OSO-C failed in the fall of 1965, the UCSD balloon activity was re-focused to study this expanding number of cosmic X-ray sources. Several graduate students, including Alan (Bud) Jacobson, Dan Schwartz, and Mike Pelling contributed to this work (Peterson et al. 1967a).

The S-57 prototype instrument was transferred from BBRC to UCSD in early 1965 to study its detailed X-ray response function. In view of the discoveries noted above, I decided it could be flown on balloons to observe sources in the hard X-ray region. A lightweight, low-power 128-channel pulse-height analyzer for balloon flights was custom built for UCSD by BBRC. This would take full advantage of the energy resolution inherent in NaI(Tl) counters. Rod Jerde designed a balloon gondola with a pointing control and the entire system was completed for balloon campaigns in the spring of 1965, as shown on figure 10. The 180 lb. (82 Kg) instrument could be flown to 130,000 ft (43 Km) altitude on a 3 million cu ft balloon. At this altitude only about 0.3 % of the atmosphere is above the instrument. Many successful balloon flights were made using this apparatus in subsequent campaigns; several results are recounted here (Peterson et al, 1967a).

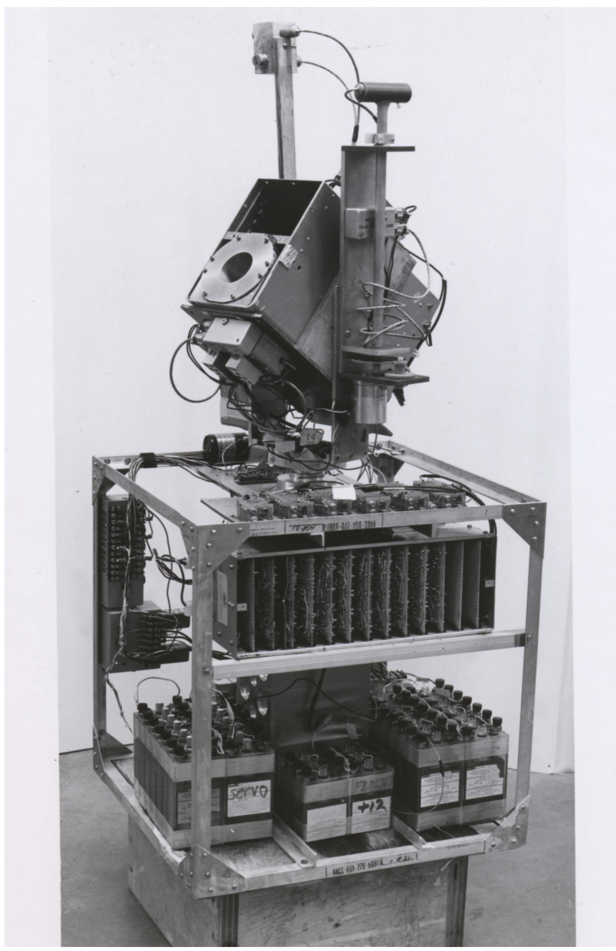

Figure 10 – The OSO-3 hard X-ray telescope mounted in a balloon gondola with an azimuth control to observed cosmic X-ray sources

The strong X-ray source SCO X-1, the "discovery source" of ASE, was observed in a June 1965 balloon flight. For the first time, it was found the spectrum extended to nearly 50 keV. These data, together with an earlier rocket result (Grader et al. 1966), are shown in figure 11. The data was fit by an exponential form, which indicated the X-rays were likely due to bremsstrahlung from a 50 million degree ionized plasma (Peterson and Jacobson, 1966a). We found little indication of non-thermal radiation at higher energies; long-term variability was noted on later flights.

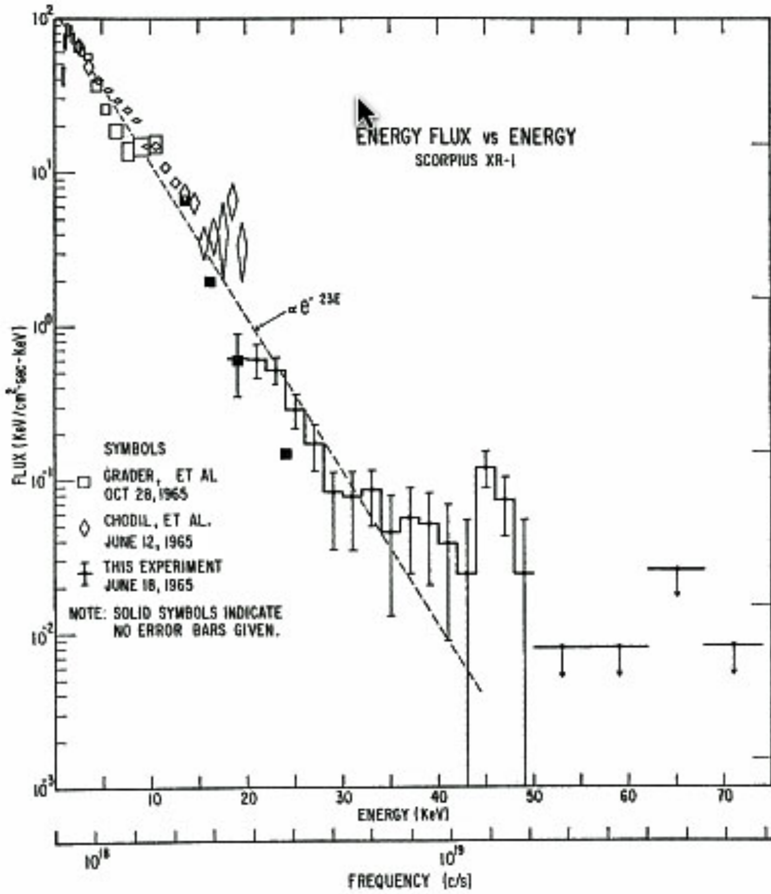

Figure 11 – The first observation of the hard X-ray spectrum of SCO X-1 showed the emission was likely from a 50 million degree ionized plasma

The Crab Nebula, the expanding remnant of a supernova explosion in 1054, was observed on a 23 September 1965 flight, confirming the initial discovery of hard X-ray emission by George Clark of MIT in July 1964, and providing a spectral measurement over the 20-200 keV range (Peterson et al. 1966b). The spectrum was of a power law form, likely due to synchrotron radiation from extremely relativistic electrons in the 10^{-4} gauss magnetic field of the Nebula. This discovery, together with other X-ray, radio and optical observations, presented considerable difficulties in understanding the acceleration and propagation of the nebular electrons. Central to resolving these difficulties was determining the size of the Nebula region at various X-ray wavelengths and the role of the 33-millisecond Crab pulsar discovered in 1968. Subsequent observations by UCSD from balloons and spacecraft contributed to this work (Laros et al. 1973a).

Low background detectors of larger area were needed for future advances in hard X-ray astronomy. To use larger area NaI detectors without increasing backgrounds due to the wide solid angle and other effects, I conceived an active collimator of CsI with drilled holes to form an aperture limiting the field of view: the ”honeycomb collimator”. The large CsI crystals required for these collimators were supplied by the Harshaw Chemical Co, who grew the blanks, machined and polished them to our specifications. The collimator pieces were mounted in a housing and photomultipliers attached. The entire assembly had to meet thermal and structural requirements for balloon or space launch environments. Several variations of this “honeycomb collimator” were developed in succeeding years and later incorporated in space instruments on OSO-7 in 1971, and HEAO-1 in 1977. John Laros, Jim Matteson and Mike Pelling were heavily involved with the later development and flight operations of the honeycomb collimator.

A test of this collimator technique was performed on 13 Sept. 1966. The detector was suspended vertically from the balloon (no pointing system), Cyg X-1 passed through the aperture during the flight and showed for the first time the hard X-ray spectrum extending as a power-law to at least 180 keV (Peterson et al. 1968).

For more general observing situations, the smaller aperture of the honeycomb collimated detectors required a new balloon gondola with a fairly precise pointing control. The system, as initially implemented, was basically an equatorial mount with magnetometers providing reference signals to keep the polar axis North during the rotation and other motions of the balloon/parachute suspension. Rod Jerde led the development of this device and its various versions; students were very involved in both the construction and field operations. These students were Dan Schwartz, Jim Matteson, Mike Pelling, and several undergraduates. Support for data transmission and collection was also evolving at the Palestine facility so experimenters had less need to provide telemetry and command systems. During most of the flights of the late 1960’s, NCAR provided a basic PCM telemetry link and computer-compatible magnetic tapes. Many sources had been discovered by late 1966; the X-ray sky at that time, along with the regions observed by UCSD balloon flights, is shown in figure 12.

Balloons carrying X-ray instruments provided the first opportunity for long-term simultaneous observations of optical and X-ray emissions from cosmic sources, important to determine if the variations correlate. The precise location of the source SCO X-1 determined by the MIT/ASE group using an Oda modulation collimator allowed the identification with an optical object (Bradt et al. 1968). In cooperation with observers using the Kitt Peak 84” telescope during a UCSD flight on 21 May 1967, we obtained simultaneous X-ray and photometric data over a 4-hour interval. This was the first such observation over an extended period (Hudson et al.1970). The X-ray flux varied a factor of two over this interval, while the optical flux changed a smaller but correlated amount. This indicated both X-ray and optical emissions were from the same emitting region. If the radiations are due to thermal bremsstrahlung, the source is transparent for the X-rays and there is some self-absorption in the optical range. Simultaneous X-ray and optical observations of SCO X-1 were also made during a 27 June 1966 flight, providing limits on γ-ray emission. Many more simultaneous observations of SCO X-1 were made by OSO-3 (Pelling 1973).

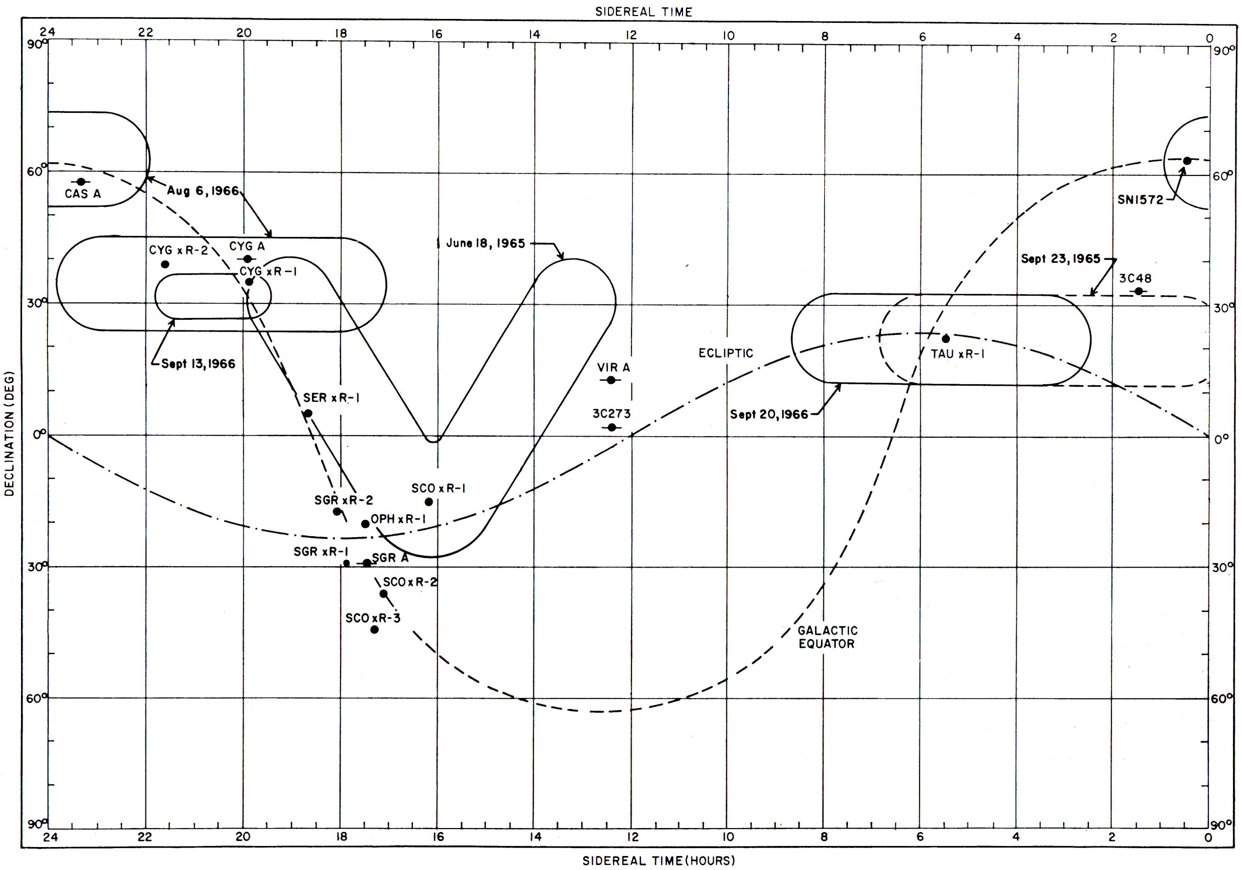

Figure 12 – Regions of the celestial sphere observed during various balloon flights in 1965 and 1966. The boundaries are at the limit of half-maximum detector response.

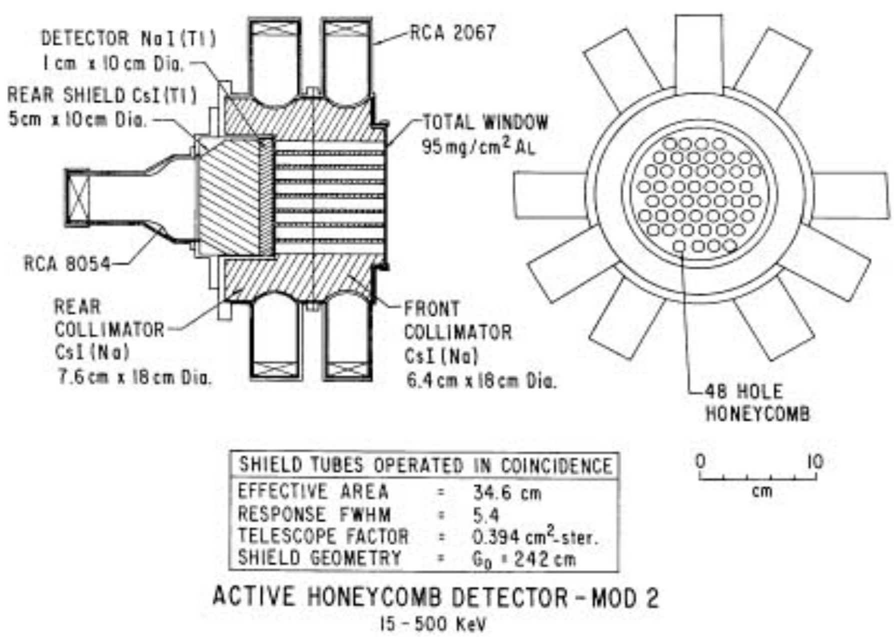

Figure 13 – The actively shielded collimated detector used in observation of Cygnus X-1.

The well and the honeycomb collimator are in electrical anticoincidence with the detector. The most complete survey of the Cygnus region in hard X-rays was on a series of balloon flights in the summer of 1969, using the honeycomb collimator shown in figure 13 (Peterson et al. 1968). The known sources in the Cygnus region and the scans obtained in a series of balloon flights are shown previously in figure 12. Hard X-rays were measured from three sources in that region: Cyg X-1, X-2 and X-3. By comparing with data from rocket and other balloon observations, it was evident that all these sources have some variability; however, the statistical significance was too low to make a positive determination of their spectral shape, except for Cyg X-1. This bright source gave more solid results. The spectral observations, along with others in both the rocket and the balloon ranges, are shown in figure 14. The hard X-ray component varied significantly over a month. Mike Pelling and Jim Matteson were the students most involved in these observations; the PhD thesis of Jim was based on this work. Later observations with the UHURU satellite showed Cyg-X1 was a binary system with a 5.6-day period and one of the binary components likely a black hole. Even later, Cyg X-1 was found to exhibit two quasi-stable modes of behavior: a high state and a low state. Many additional observations of the time variability and spectral shapes of cosmic X-ray sources were obtained with the UCSD hard X-ray instrument on OSO-7.

Figures 15 and 16 show the balloon gondola for the honeycomb collimated detector and the balloon layout for a typical launch.

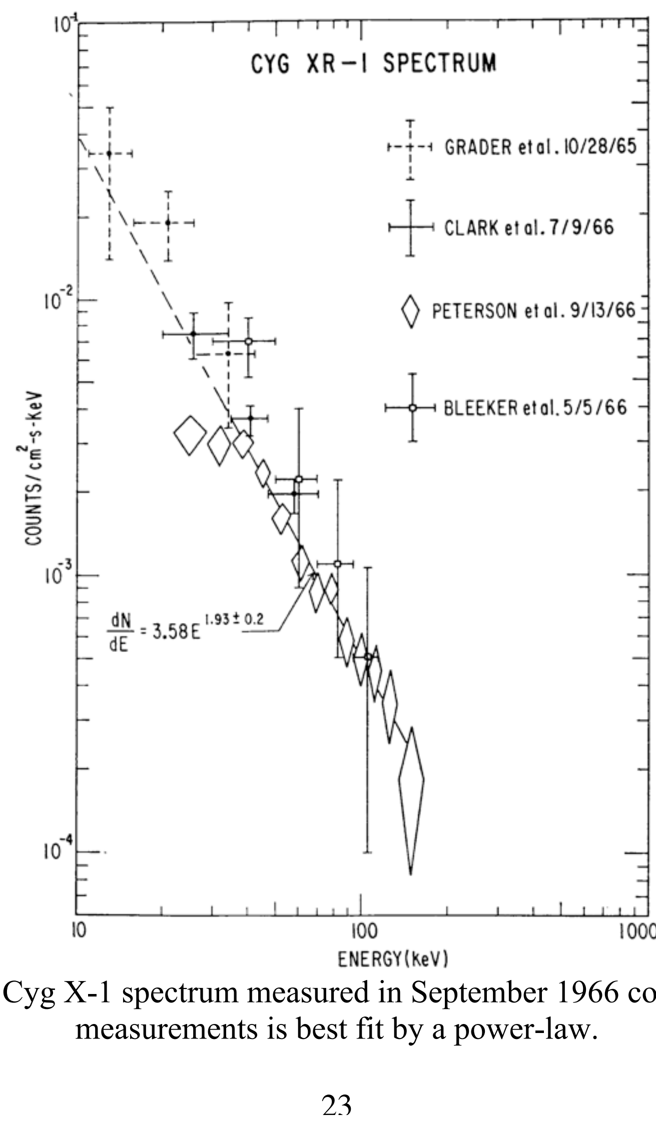

Figure 14 – The Cyg X-1 spectrum measured in September 1966 compared with other measurements is best fit by a power-law.

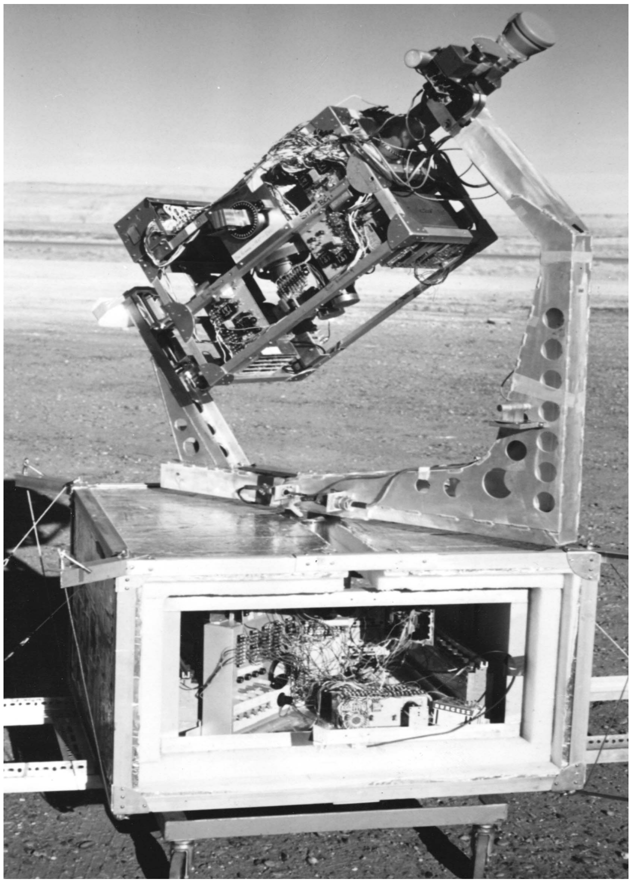

Figure 15 - The gondola and pointing control designed for the honeycomb collimated detector system. The pointing control is a polar mount referenced to the local latitude.

Figure 16 – The launch lay-out for the balloon parachute and payload for a typical balloon flight after inflation and just prior to launch.

The higher sensitivity provided by the honeycomb collimated hard X-ray detector permitted observations of some of the brighter extra-galactic sources. Several observation of the Seyfert Galaxy NGC 4151 showed the spectra to about 100 keV to have a power-law form indicative of a non-thermal X-ray emitting process ,and to have some variability (Paciesas et al. 1977). Additionally upper limits on a number of likely extra galactic sources, such as M87, Cen A, and the Quasar 3C 273 were obtained (Laros et al. 1973b). In addition to those already acknowleged, a number of students, including Duane Gruber, Richard Mushotsky and Bill Wheaton made major contributions to the balloon program.

B – Search for Gamma-Ray Lines

The search for discrete γ-ray lines due to postulated nuclear processes in sources, such as the Crab Nebula, required a significant resolution improvement over that obtained with NaI scintillation counters. By the mid-1960's, cooled solid-state detectors for X- and γ -rays were becoming available. Accordingly, we obtained a lithium-drifted germanium detector, Ge(Li), of about 10 cm^2 area and incorporated it into the anticoincidence collimator of the S-57 prototype unit for exploratory balloon flights. The detector resolution was about 3.5% at 122 keV as measured with a Co^{57} radioactive test source, about 10 times better than obtainable at this energy with a NaI counter! To prevent the lithium from diffusing back to the surface, it was necessary to maintain the detector at liquid nitrogen temperatures continuously after the initial drift. The detector was shipped to UCSD with a cold finger and a Dewar, which was incorporated into the flight system. The original S-57 balloon gondola and pointing control, as modified for the Ge(Li) detector system, are shown in (figure 17).

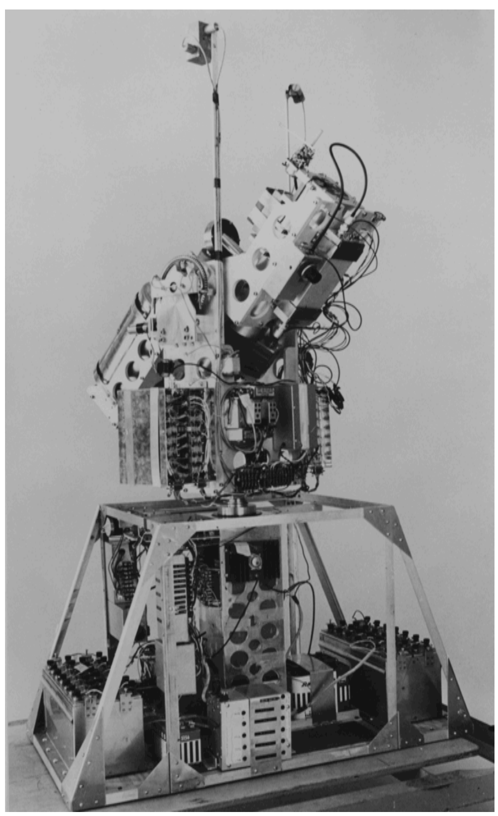

Figure 17 – The gondola containing the 10 cm^2 Ge(li) detector designed to search for nuclear gamma-ray line emission in the 20-300 keV range

The particular objective of this experiment was to search for γ-ray lines expected if the approximate 55 day decay of the light curve, immediately following the explosion, which formed the Crab Nebula, was indeed due to radioactive materials it had produced. It had been discovered that a particular isotope at the high end of the periodic table, Cf^{254}, has a half-life of about 60 days. It seemed possible that this isotope, along with several others, could be synthesized by the r-process, and that the radioactive decay of these isotopes provided the energy for the initial decay phase. In that case, there would also be long-lived isotopes produced, some decaying with thousand-year lifetimes and producing the γ-ray spectrum shown in fig. 18 (Hoyle and Fowler, 1960). The flight of 23 July 1967 was dedicated to observe the Crab Nebula and search for these lines. Only upper limits were found at a level about 10^{-3} ph/cm^2-sec, putting constraints on the Cf^{254} hypothesis. This work became the thesis subject of my first PhD student, Bud Jacobson, John Laros also worked with Bud on this project (Peterson and Jacobson, 1970).

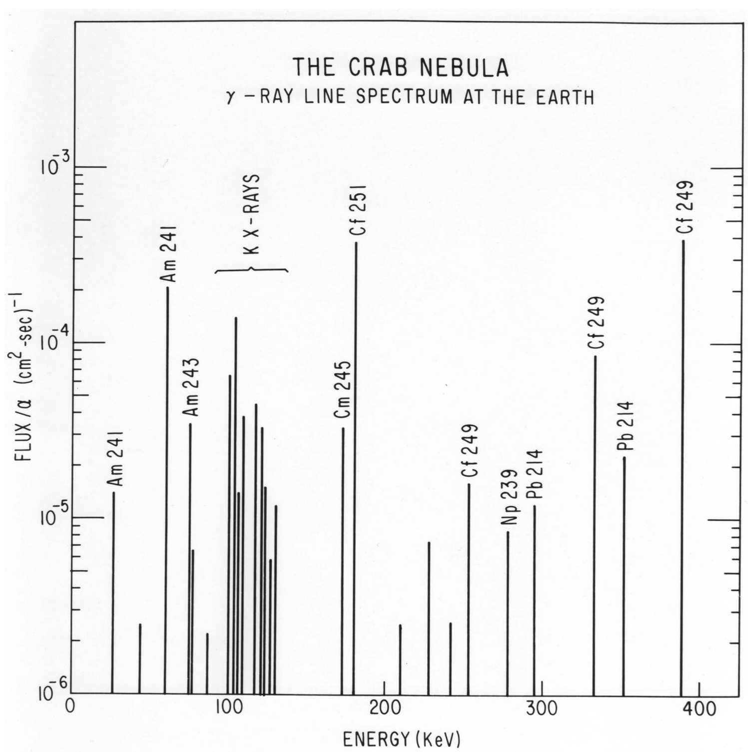

Figure 18 – The spectrum expected from the Crab nebula based on the Cf^{254} hypothesis to explain the 55 day decay of the light curve after the initial explosion.

Since the time of these investigations, the Cf^{254} idea has been discredited. We know now that Type I supernovae are due to core collapse of massive stars with the initial light curve associated with the Ni^{56}—Co^{56}—Fe^{56} decay chain. In a later stage, the expansion of the Crab nebula was powered by the 33 millisecond rotating neutron star formed from the collapse. After these discoveries, some of my later students studied aspects of the pulsar, and made further observations of the spectrum of the Nebula and its size in hard X-rays.

This apparatus was flown during several campaigns in the 1967/68 period searching for γ-ray lines in the 20-250 keV range from known X-ray sources. Although only upper limits for line emission of about 10^{-3} ph/cm^2–sec were set for several sources, the better resolution allowed determination of more precise hard X-ray continuum of several sources. This information is needed to understand the physics of the emitting region.

C - Solar Gamma Rays

Solar Cosmic rays reaching the earth due to energetic particle acceleration were known to occur during solar flares associated with sunspot group by processes similar to those producing hard X-ray bursts. As a consequence, detection of hard X-ray or γ-ray emissions from the quiet Sun (when no sunspots are visible on the solar disc) was important to determine if particle acceleration processes or radioactivity were present. No emissions were observed in the 50 keV to 10 MeV range during several flights, placing severe limits on such processes on the quiet Sun (figure 19). This graph also shows the dramatic improvement in sensitivity obtained using honeycomb collimators and other advanced detectors over those of OSO-1 era (Peterson et al. 1966c).

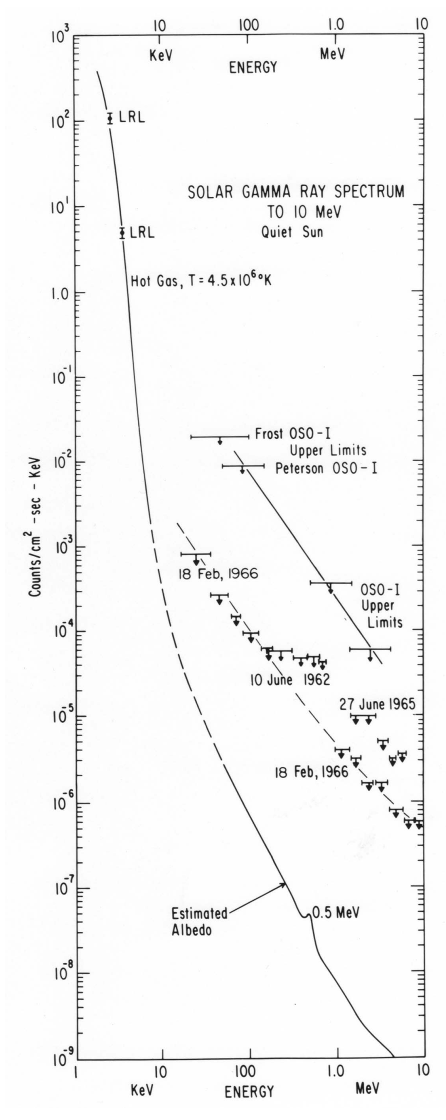

Figure 19 – Measurements and upper limits on the quiet sun gamma-ray spectrum determined from a series of balloon flights in 1966, compared with previous observations.

VII - The ERS SERIES

We had gained insights to the application of an isotropic detector operating in the MeV range through the preliminary analysis of the OSO-1 data and through the understanding of γ-ray produced background and other effects from the series of balloon flights from Dateland in the summer of 1963. It became an important objective to find an opportunity to put such a counter on an appropriate space mission. This could verify the presumed isotropic cosmic background fluxes discovered in the MeV range by the Ranger-III, improve on the limits obtained by OSO-1 and could continuously monitor the Sun for solar flare hard X-Rray events. I became aware of a number of possible opportunities through my advising role in NASA committees. Some were auxiliary or "fill-in" on missions and I submitted several proposals, none of which was accepted. The real possibility came outside of NASA.

I had maintained contact with Jim Vette after he left GD/A in 1961 for the Aerospace Corporation in Los Angeles where he investigated radiations in the space environment and their effects for various defense-related projects. At that time, the Air Force operated an Environmental Research Satellite series (ERS) in conjunction with other DOD programs, including the Vela nuclear event detection project. Jim suggested an opportunity to participate in some ERS missions, which used small piggyback spacecraft orbited as attached payloads on selected launches. These small satellites, known as the Octahedral Research Satellites (ORS) were being constructed at TRW, apparently in a "Skunk Works" type operation. At least two of the ERS missions would carry a series of detectors designed to determine energetic radiations in orbits of interest to the Vela program. Vette suggested UCSD provide γ--ray counters operating roughly in the 30 keV to 10 MeV range. The NaI(Tl) counter on ERS-17 was of a phoswich type, similar to that on OSO-1; the detector on ERS-18 was based on the design shown in the figure 6. On the ERS-18, the NaI(Tl) crystal measured 7.6 cm diameter and 5.5 cm length, was in anti-coincidence with a 1.0 cm plastic scintillation particle shield. The isotropic geometry factor was 67 cm^2. The counters were assembled in our lab and integrated into the spacecraft at TRW. Paul Brissenden participated in the integration and checkout. The spacecraft, shown in figure 20, was a simple octahedral structure about 30 cm on side, covered with solar panels. A low power transmitter drove a dipole antenna. The NaI crystals were an appreciable fraction of the total mass of the system.

During the Vela launch phase, the ERS were injected into highly elliptical orbits at about 32 degrees inclination. Apogees were about 112,000 Km, the perigee of ERS-17 was only 200 Km; that of ERS-18 8400 Km. The inner and outer-trapped radiation belts were traversed due to the low Earth orbits. The spacecraft were well outside the Earth's magnetosphere for large time intervals. Since the Vela project was classified, and none of us at UCSD had proper security clearance, we could not know the launch schedule. Jim gave us hints like "better deliver the detectors soon"! The ERS-17 was launched in July 1965, the ERS-18 April 1967.

Raw analog magnetic tapes received at the various STADAN stations were sent directly to UCSD for reduction and analysis. The Air Force funded the effort at UCSD. We produced maps of the space weather as obtained from the various particle and radiation detectors in the payload. The playback analysis system, based of the one used for OSO-1, was modified by Paul Brissenden and Louis Huszar. The set up was operated by an enthusiastic group of part-time undergraduates, sometimes on a day and evening schedule. One of these students, Fred Duttweiler, continued full time in the group until his retirement.

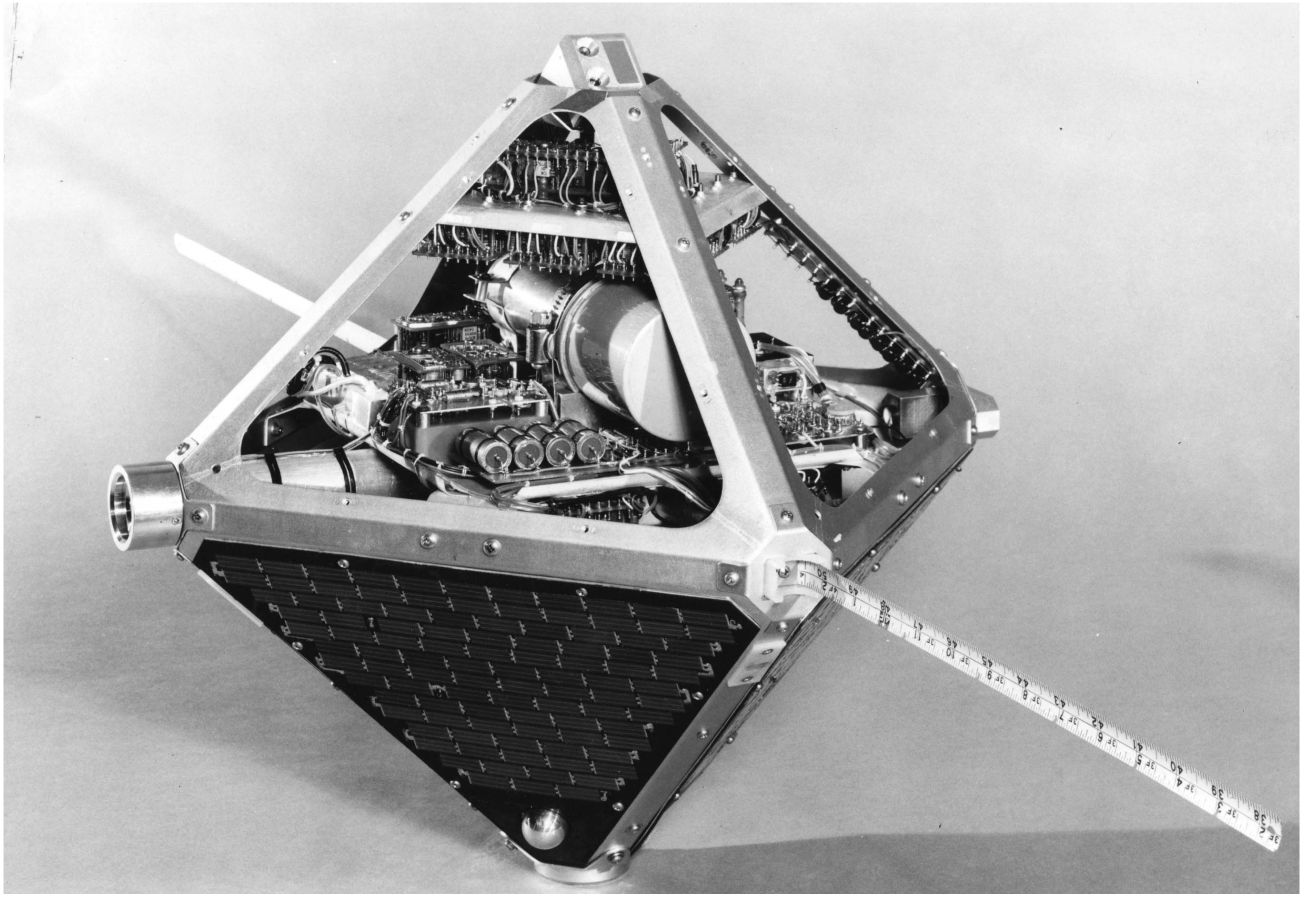

Figure 20 – The Environmental Research Satellite 17, the scintillation counter with its anticoincidence shield was an appreciable fraction of the spacecraft weight.

The principal result of interest to me was a measurement of the cosmic background γ-ray spectrum originally detected by Ranger III. Since the detector only had about 2gm/cm^2 of light material surrounding it, and the Earth subtended a small solid angle, local background effects were minimized. The results on the diffuse cosmic γ-ray spectrum are shown in figure 21 (Vette et al. 1970a). I presented these results at the 3rd Texas symposium on Relativistic Astrophysics and at the 1970 Rome IAU Symposium, causing considerable controversy (Vette et al. 1970b). The issue was the role of long-term induced radioactivity in the detectors. To my knowledge, the matter is still open. The spectrum of diffuse γ-rays in the low MeV range, if they exist at all, is not clear.

A burst of solar γ-rays, with a spectrum extending to several MeV, was detected during the giant white-light flare of 7 July 1967. Gamma-ray lines due to energetic protons accelerated in such flares and interacting in the photosphere had been predicted by R. Lingenfelter and R. Ramaty. They reviewed the results in a later paper (Ramaty et al. 1975). Duane Gruber did much of the analysis of the ERS data, and presented the flare results at a conference on solar activity at GSFC in 1974. We knew this was an important result but, unfortunately, the low bandwidth of the ERS telemetry, like that of OSO-1, did not allow for high resolution data transmission. Ed Chupp at the University of New Hampshire, had a similar counter on OSO-7, and later detected predicted γ-ray lines at 0.5 and 2.2 MeV during the large flares of 4 and 7 August 1972 (Chupp et al. 1973). These results gave many new insights into the acceleration and transport of energetic particles in the solar atmosphere and photosphere

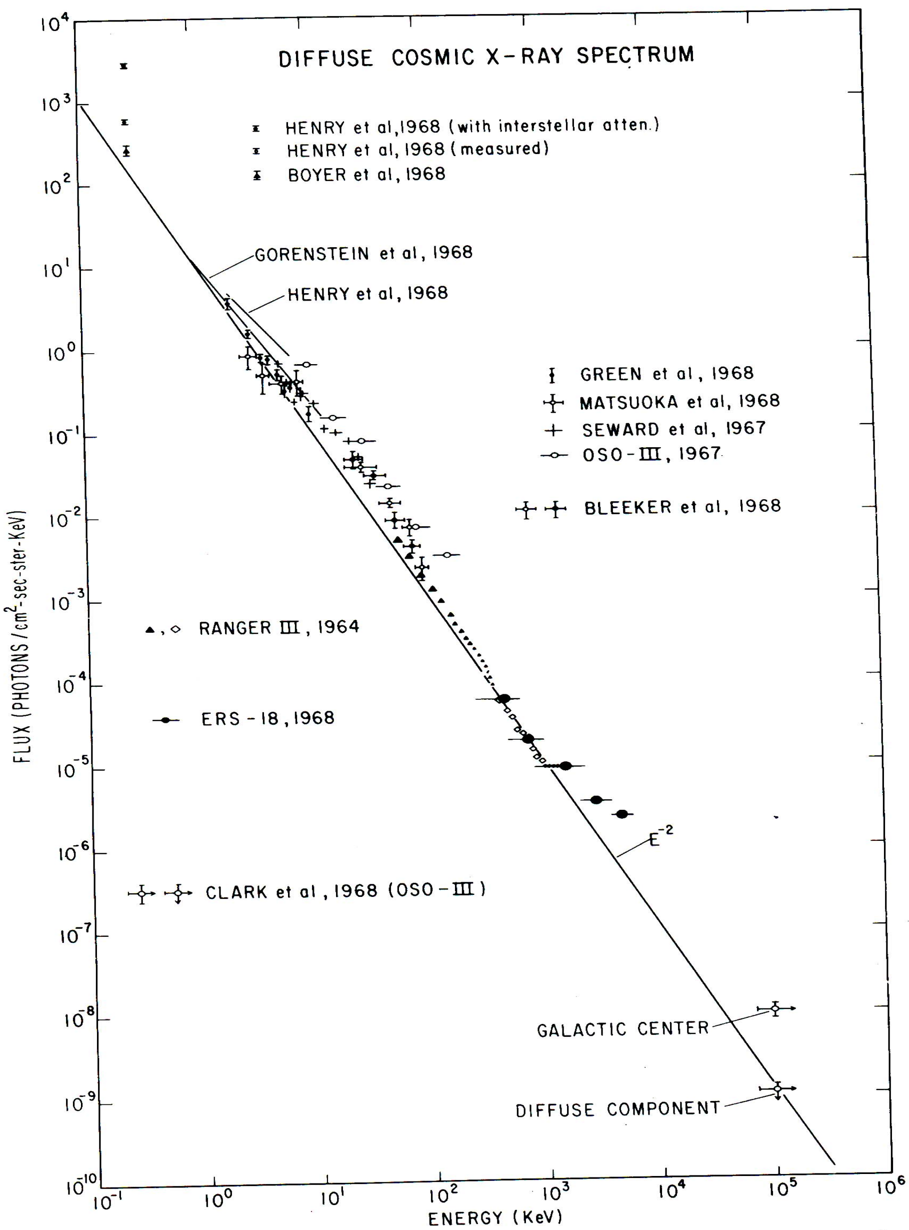

Figure 21 – The diffuse cosmic gamma-ray spectrum measured by a number of instruments over a wide range of energies in the late 1960's. The ERS 18 provided the best data points at low gamma-ray energies for many years.

VIII – LUNAR AND COSMIC NUCLEAR GAMMA RAYS

A- Gamma Ray Detector Studies

Concurrently with the development and application of detectors for hard X-rays, and despite considerable technical problems, we pursued techniques extending into the 300 keV to 10 MeV energy range. I had particular interest in this work because of the possibility of γ-ray lines due to nuclear processes in astrophysics. Observations in this energy range are particularly difficult because the primary interaction of MeV γ-rays is the Compton effect, where, as discussed earlier, the incoming photon scatters an electron in the material while losing only part of its energy. Multiple scatterings occur before the photon energy is reduced enough to be absorbed. Since the Compton cross section is low, large detector volumes and thicker shields are required. Several configurations, taking these effects into account, were flown on balloons in the 1964 to 1970 period; a typical version is shown in figure 22. This work permitted extension of the spectral measurements of X-ray sources into the γ-ray region and searches for γ–ray lines.

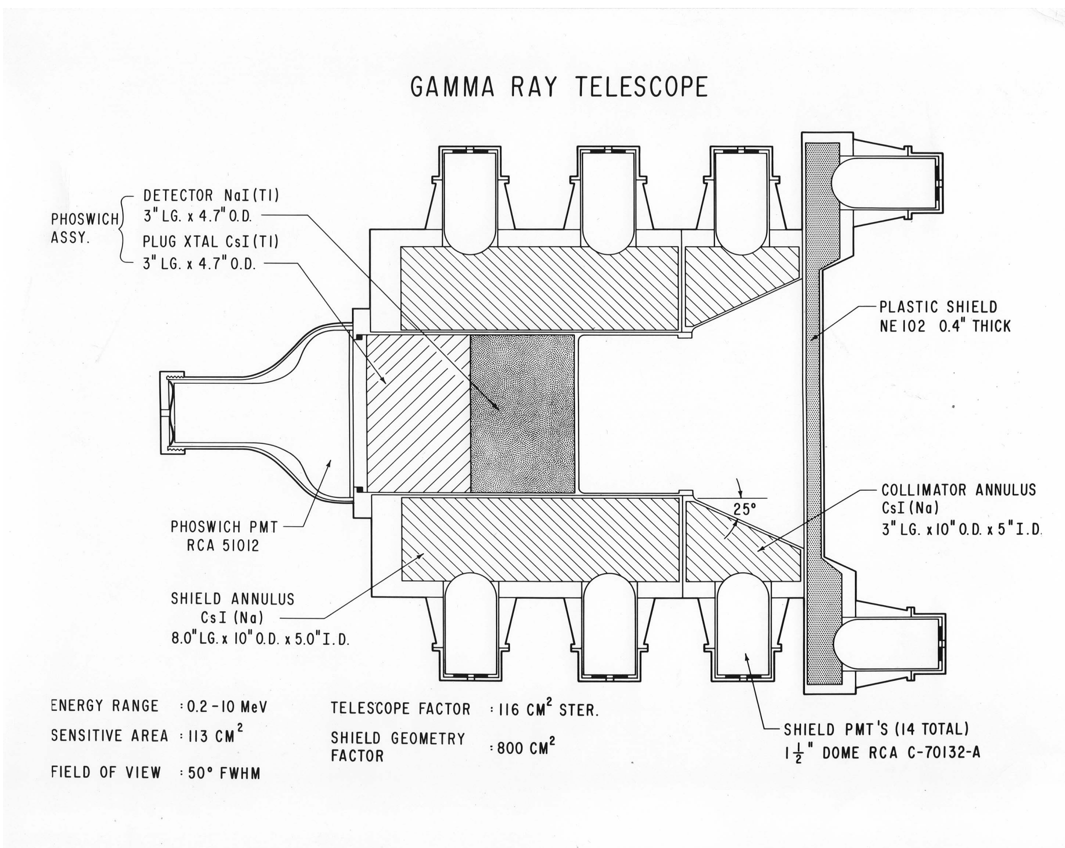

Figure 22 – One of several versions of an experimental gamma-ray telescope developed for the 0.3-10 MeV range using the active anti-coincidence technique.

B - The Compton Telescope

The development of an advanced balloon-borne Compton Telescope for observations of γ-rays in the 0.5 -10 MeV range was also investigated. A graduate student developed a computer simulation of various geometries and configurations. From this, I determined that a device having detector planes of at least a square meter, separated by several meters, with elaborate anticoincidence and timing, was required to obtain the sensitivity and angular resolution. Further effort on this class of instrument was dropped because the extensive resources required were beyond the scope of the UCSD SR&T program. However, Steve White at UC Riverside, and Volker Schönfelder at MPE Garching, flew versions of Compton Telescopes on balloons. Based on his experience, Schönfelder later developed the CompTel instrument for the Compton Gamma-Ray Observatory, launched in 1991, which produced many notable discoveries.

C - Cosmic Ray produced Nuclear Gamma Rays

Cosmic rays interactions also transform the nuclei of detector materials, producing both short and long-lived isotopes. This production, besides causing another unwanted detector background, is of particular interest to cosmo chemists as an indication of the age and exposure history of meteorites and planetary surfaces. The adage "one investigator's signal is another's noise" certainly applies here! Jim Arnold and I had similar interests in γ-ray spectroscopy, even if for different scientific objectives. Jim, in conjunction with Al Metzger at JPL, was trying to repeat the Ranger-III experiment with spectrometers on either pre-lunar landing missions or in conjunction with the Apollo moon project. Arnold was one of a group of four eminent scientists lobbying to get scientific investigations directly incorporated into the lunar landing program. Arnold and I cooperated on two activities.

The first was incorporating a γ-ray spectrometer into the lunar science program. The isotropic NaI counter we developed for the study of atmospheric γ-ray, shown in figure 6, became an engineering model for a spectrometer proposed for the Surveyor and other pre-lunar landing missions. Despite NASA 's initial reluctance to accept any experiments that might jeopardize the landing schedule, the instrument was accepted for flight on Apollo missions 15 (1971) and 16 (1972). The detector was mounted on an 8.3 m boom extended from the Service Module to reduce γ-rays emanating from the spacecraft. The service module, with one astronaut on board, orbited the Moon at a low altitude during the Lander's excursion to the surface. The γ-ray spectrometer, along with X-ray instruments, made a map of lunar X- and γ-ray emissions to determine the chemical composition of the lunar surface. During the trans-lunar period of the mission, the spectrometer measured the diffuse component of cosmic γ-rays, and obtained precise spectra in a low background environment.

Our second collaboration was on a number of balloon flights using the isotropic counter surrounded by massive amount of various materials to study the direct production of γ-rays by cosmic rays. The earth mineral complex called dunite has a composition likely similar to one of the possible lunar surface minerals, depending on the geological history of the moon. After a nearly 9 hour exposure to the full cosmic ray beam on a balloon flight over Palestine on 11 April 1965, the 2.2 MeV line due to deuterium was observed, however no evidence of γ-ray lines due to oxygen were observed, an unexpected result. A general decay of the background continuum was noted immediately after the experiment was returned to the ground, indicating some short-lived isotopes were produced. On 2 February 1966, the detector, enclosed in a 30 cm iron cube, was flown, also for another 9-hr exposure to cosmic rays. This clearly showed production of the 0.51 MeV annihilation line, and the 0.850 and 7.6 MeV γ-rays from neutron capture in Fe. These results were useful for the interpretation of the γ-ray spectra measured by the Apollo from the lunar surface.

IX - The OSO-7

A – Proposals and Development

The NASA Announcement of Opportunity (AO) to submit instrument proposals for the upcoming OSO-H (OSO-7 after the launch) was released early 1966, with a due date of 1 July. During the five years since OSO-1, many advances were made in the understanding of solar flares and the role of energetic particles in the flare mechanism. No instrument specifically observing hard X-rays was included in the OSO-2 payload; and the OSO-3, which carried the UCSD 7-190 keV telescope, had yet to be launched. I decided to propose a "Hard Solar X-Ray Monitoring Instrument" for a wheel compartment. This experiment would also take advantage of the improved technologies developed under the UCSD SR&T grant. It was selected during the initial review.

However, there were not enough suitable proposals to make up a worthwhile instrument complement in the wheel. Consequently, several other investigators and I urged NASA to release a supplementary AO, specifically soliciting proposals for solar and cosmic X and γ-ray instruments for the wheel. I had the concept that sources would be better discovered and identified in the soft X-ray region where the relative sensitivity was higher; the OSO-H would determine extended spectra and other properties of these sources and therefore the physics of the emitting region. The second-generation instrument I proposed, would study the time variability and spectral properties of X-ray sources in the 10-300 keV range based on the development of the honeycomb collimated detectors. This experiment was selected by the second NASA review, as well as a spectrometer for 0.3-10 MeV Solar flare γ-rays proposed by Ed Chupp, and a multi-layer proportional counter to observe time structures of cosmic X-ray sources in the 1-60 keV region proposed by George Clark. With this new selection, there now was a good set of complementary instruments for the OSO-H wheel.

Having these two major instruments on a single NASA mission required a considerable build-up of personnel and resources in my group. It was my philosophy for these instruments that advanced detector systems often cut new technical ground and should be built in-house. Electronic systems, while complex and extensive, did not require new technologies and could be sub-contracted. I decided the OSO-H solar instrument could be contracted out as a unit since the detectors were well specified based on OSO-3 and balloon experiments. However, we built the honeycomb collimated detector for the cosmic X-ray instrument, but sub-contracted the electronic system. In 1967, I hired Bob Farnsworth, from GD/A, to be the full time project engineer needed to manage both in-house and subcontract activities. Bob oversaw the solicitation of proposals from commercial organizations.

Our group expansion also resulted in lab and office space problems. Instrument development and data analysis labs were scattered over several levels in the Physics building, data playback operations were in an adjacent building basement, and the large balloon gondolas were being assembled and tested in a Quonset across campus. These, as well as other structures, remained on the former Marine Camp Mathews after the transfer to UCSD in 1965. An opportunity to consolidate these activities came when space became available in a new research building in Muir College where we moved in the spring of 1969. The disadvantage of this move was the loss of casual daily interactions with the core of the Physics Department. The unexpected positive was, in the following years, the migration to the new building of the other Astrophysics and Space Science faculties and their groups.

At the peak of the OSO-H instrument development, I had about 30 people working with me, among them: Hugh Hudson, now a Research Scientist, two Postdoctoral Scholars, 6 graduate students, 8 full time technical and administrative staff and an equal number of undergraduates involved in data analysis and laboratory work. The scientific oversight during the design, construction and test of the OSO instruments, as well as setting-up the data processing and analysis, presented opportunities for recent PhD's who had previous experience in balloon, rocket or space experiments. Dayton Datlow, from the University of Chicago, filled this function on the solar X-ray project and Mel Ulmer, from the University of Wisconsin worked on the cosmic X-ray instrument. These postdoctoral fellows played a major role in the analysis and publication of scientific results from the mission. Bill Baity, who had an advanced degree from Maryland and experience at GSFC, was also recruited. In addition, Geoff Burbidge and I shared the support of several postdoctoral fellows working on theoretical problems in high energy astrophysics.

The OSO-7 was launched 29 Sept 1971. Once again, the third stage misbehaved, so the planed 550 km circular orbit was not achieved. Instead, the spacecraft was put into a 321x572 km, 32º inclination orbit. This resulted in a higher and more complex background that reduced the sensitivity for detection of cosmic fluxes. Still, the spacecraft and instruments operated well until the second tape recorder failed in May 1973, and many unique scientific results were obtained. Because of the lower orbit, the OSO-7 re-entered the atmosphere on 29 July 1974.

B –The Cosmic X-Ray Instrument

The honeycomb collimator and detector assembly for the cosmic X-ray instrument was designed and built in our lab. BBRC was selected to provide the instrument electronic sub-system, the ground test equipment, and support during qualification testing. Ed Stephan, a UCSD Physics undergraduate and full time employee, made a major contribution developing techniques for encapsulating and mounting the phototubes. He also operated the test equipment and set-up the data reduction computers. An additional programmer and a number of undergraduates built and operated the data system before and after the launch. The instrument is shown on figure 23.

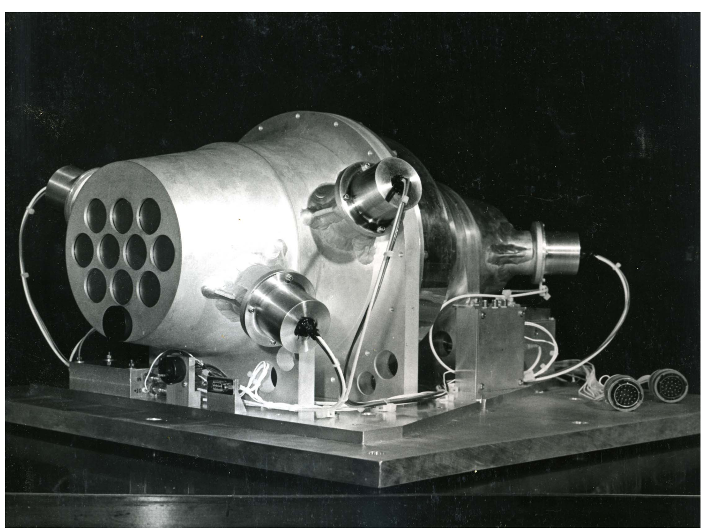

Figure 23 – The hard X-ray telescope with an active anticoincidence honeycomb collimator flown on the OSO-7 spacecraft.

Because we obtained principal results from OSO-7 after 1972, I only intend here to outline them. An early UHURU catalog identified 161 sources (Giacconi et al. 1974). We were able to detect about 40 of these in hard X-rays, many of these with enough significance to make spectral form determinations. These sources fell into broad categories: supernova remnants, including the Crab; binary stellar systems with a compact object such as a neutron star or a black hole; transients of a unknown nature at the time; and extra galactic sources usually associated with an active galaxy or a quasar. Figure 24 shows a compendium of spectra from the unique and extensively studied binary X-ray source: Her X-1 (Manchanga, 1977). The OSO-7 data points are among the most precise (Ulmer et al. 1973) and are compared with a reference thermal bremsstrahlung emission spectrum with kT=8 keV.

Mel Ulmer was the lead research scientist on the data analysis, Bill Baity and many students made contributions. As many as 40 papers on a variety of sources were published in the refereed literature. Richard Mushotzky and Bill Wheaton obtained their PhD theses from the data.

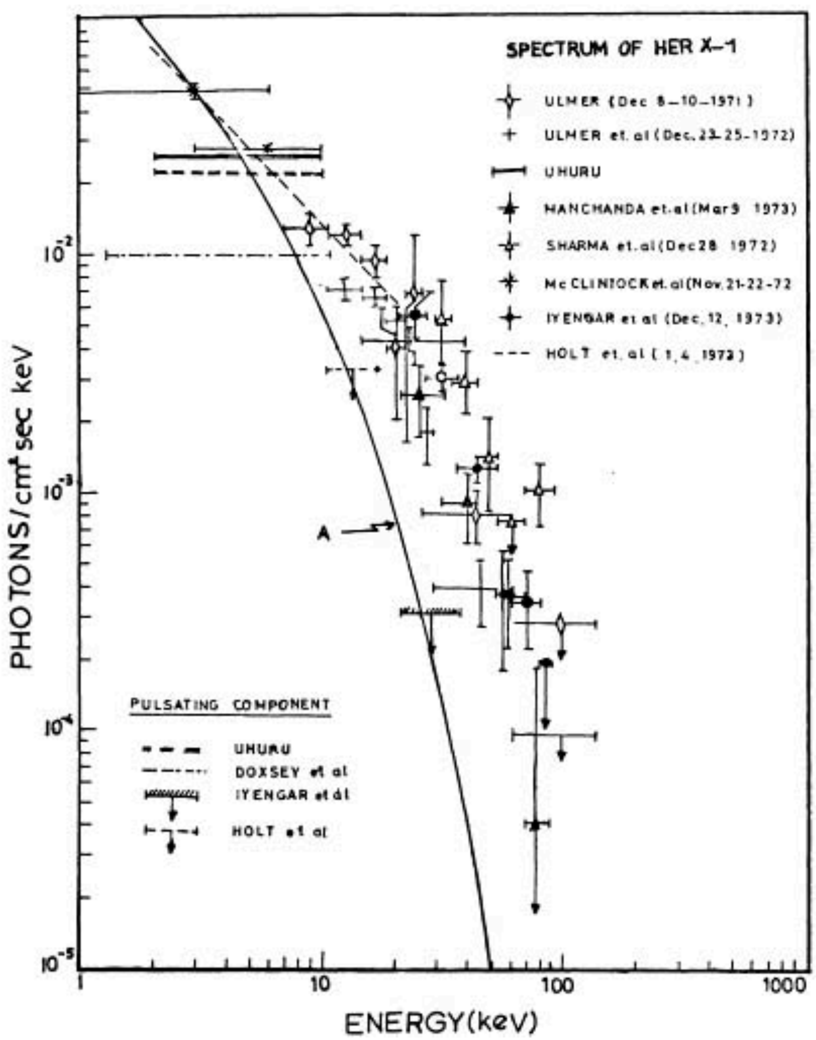

Figure 24 – Many researchers observed the spectrum of Her X-1. This figure includes our OSO-7 observations with both pulsed and non-pulsed components shown.

C- Solar X-ray Experiment

The Analog Technology Corporation, founded by former JPL employees, was selected to design and build the solar X-ray instrument. They also provided the ground support equipment, and performed the qualification and test of the instrument. Dave McKenzie, who had written his PhD thesis on solar data from OSO-3, contributed his experience base to design the detectors. The objective was to increase the dynamic range, avoid saturation and pulse pile-up during intense events, as well as obtain higher spectral coverage and resolution. Two detectors were needed for these goals: a thin Be window proportional counter covering the 2-15 keV range and an active collimated NaI counter covering the 10-320 keV range (Harrington et al. 1972). The apertures were fan-shaped to maximize exposure to the sun each 2-sec OSO wheel rotation. The time resolution goal was 0.5 sec.

Due to the large dynamical and energy range of the instrument, we were able to study the spectral evolution of a large number of solar flares and to separate non-thermal and thermal components. For example, during a flare on 16 Nov. 1972, hard X-rays from plasma initially heated to 20 million degrees by non-thermal electrons completely energized the soft X-ray emission occurring after the primary event (Datlowe et al. 1974). The plasma emitting soft X-rays was heated in about a minute and the flux decayed in about 5 min. The dynamics allow one to distinguished between various density regions for the energy transfer and the cooling processes.

With this instrument, we were able to do the first study of weak sub-flares in soft X-ray emission. From a sample of nearly 200 flares, we found these coronal-like events had a characteristic impulsive rise time of about 1 min, and a long-term slow decay, typically 15 min.

Our instrument provided important complementary data (Datlowe and Peterson, 1973) for the interpretation of the major discovery made by the solar γ–ray spectrometer of Ed Chupp (Chupp et al. 1973). This was first confirmed measurement of discrete γ–ray lines from nuclear processes in large flares at 2.2 MeV due to deuterium formation, and at 4.4 and 6.13 MeV due to excited states of carbon and oxygen. Dayton Datlowe and Hugh Hudson led the analysis and interpretation of data from the solar X-ray instrument; Mike Elcan obtained his PhD thesis from statistical studies of solar flares X-ray emissions

X - EPILOGUE

By the launch of OSO-7, our scientific goals were clear, technological developments were underway and a core group of support personnel was in place to allow the UCSD High Energy Astronomy group to make forefront contributions in the decades ahead. In the mid-1970’s, I made the personal decision to reduce my effort in solar physics research and focus on cosmic X-ray and γ-ray astronomy. Hugh Hudson and Dick Canfield then led the UCSD group in Solar Physics.

As co-investigators with Jim Arnold for the Gamma-Ray Spectrometer flown on Apollo flights 15 (1971) and 16 (1972, we contributed the concept of the detector that was re-engineered by JPL. Besides measuring γ-ray lines due to radioactivity from the moon’s surface when the Service Module was in lunar orbit, the trans-lunar phase presented an opportunity to measure the diffuse cosmic γ-ray spectrum in a low background situation. A serendipitous γ-ray burst provided the most precise spectrum of one of these events available at the time.

Mike Pelling led a collaboration with Minuro Oda's group at the Institute of Space and Astronomical Sciences (ISAS) in Japan to use a balloon-borne modulation collimator to image the hard X-ray emitting region of the Crab Nebula. A collaboration between Walter Lewin of MIT and I developed a follow-on of the OSO-7, the Hard X-ray and Gamma Ray Instrument for the first High Energy Astronomical Observatory (HEAO-1). Rick Rothschild, who came to UCSD from the GSFC in 1977, led the UCSD data analysis effort. The mission, launched 12 August 1977, produced many new results on galactic and extragalactic sources, and the first catalog of hard cosmic X-ray sources. This catalog was not superseded for nearly 25 years.

By the late 1970's, about 25 Faculty in various academic departments at UCSD were engaged in astrophysics and space related research. Two major projects were underway: the Faint Object Spectrograph for the Hubble Space Telescope and a major instrument on the upcoming Gamma-Ray Observatory. To provide a focal point for the diverse research activities and a management structure adapted to the large technical projects, the UCSD administration created an Organized Research Unit, the Center for Astrophysics and Space Research (CASS). Margaret Burbidge was the founding director. After Margaret second term in 1988, I became director through 1997.

The Gamma Ray Spectroscopy Experiment (GRSE) for the GRO was proposed in February 1978 to follow the UCSD HEAO instrument but using large volume Ge cooled detectors to obtain much higher energy resolution. Jim Matteson led the development of the instrument and detector systems. An international consortium of scientists contributed instrument components and operations and data analysis efforts. After the Phase A study, it was not included in the final payload. However, sufficient funding was provided by NASA to develop an advanced instrument based on a 12 detector cluster of Ge modules in an active anticoincidence shield and collimator. This very complex instrument, called HEXAGONE, was flown on several balloon flights searching for γ-ray line emissions, particularly from the supernova SN 1987a. A variation of this instrument was built and used by Mike Pelling in collaboration with Bob Lin of UC Berkley to search for solar γ-ray line emissions using long duration Antarctic balloon flights. This formed the model for the High Resolution Gamma-Ray Spectrometer on the Ramaty High Energy Solar Spectrometer and Imaging space mission launched in 2002.

Several years later, we worked on a proposal for the X-ray Timing Explorer (XTE). At that time, NASA's Astrophysics Program Office informed me I could not be PI on proposals for two major instruments. I decided that Rick Rothschild should become PI on the XTE, and I would be PI on the GRO proposal. As I indicated, the instrument for the GRO was not excluded during the final payload selection.

The Hard X-Ray Timing Experiment (HEXTE) on the Rossi X-Ray Timing Explorer was launched 30 December 1995. This instrument produced many new results on the time and spectral variations of galactic X-ray sources, cyclotron lines from an accreting neutron star, spectra of extragalactic objects. It performed almost flawlessly for over 16 years until the spacecraft was turned off in January 2012. Rick Rothschild led the data analysis.

Writing this paper brought back many memories. I was fortunate to be at the beginning of a new field of astronomical research, to have seen NASA's creation, and being part of the Space

Science community as it matured into the main stream. “Physics with a screwdriver” was my style. But by about 1970, I was involved in so many activities that I no longer had the time to do hands-on work in the lab. That was a frustration that I had to accept and was compensated by the dynamics of the group I created and the contacts made with scientists in the U.S. and abroad.

But most of all, I feel privileged to have been working with a group of talented and dedicated people; together, we shared in disappointments and successes. I am very pleased of the large body of discovery and research we accomplished and the achievements of many of my former students and colleagues.

ACKNOWLEDGMENTS

I want to thank Hale Bradt for organizing the session “50 Years of X-Ray Astronomy” at the January 2013, AAS meeting in Long Beach California and for encouraging those who made presentations to write a contribution for the AIP Archives. This paper is the result of his initiative. I thank Fred Duttweiler, Duane Gruber and Ed Stephan for clarifying my memories of the formative days of the UCSD group. I particularly owe many thanks to Mike Pelling, one of my early PhD students, who accepted to review this paper and provided many valuable comments. I thank Rick Rothschild for his comments after the distribution of an earlier version of the paper. I must credit my wife, Joele, for her work in the production and review of this personal history.

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