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GRANT NSG-7592



High Resolution X- and Gamma-ray Spectroscopy
of Cosmic X-ray Sources

FINAL REPORT

February 1, 1979 - April 30, 1983

Submitted by

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I. Introduction

This grant, NSG-7592, and an accompanying grant (NSG-7527, from NASA's Solar Physics Division) provided the funds to develop, fabricate and fly a balloon-borne X- and γ -ray instrument. This instrument has the highest energy resolution of any instrument flown to date for measurements of solar and cosmic X-ray and γ -ray emission in the 13 - 600 keV energy range. The purpose of the solar measurements was to study electron acceleration and solar flare energy release processes. The cosmic observations were to search for cyclotron line features from neutron stars and for low energy γ -ray lines from nucleosynthesis.

The instrument consists of four 4 cm diameter, 1.3 cm thick, planar intrinsic germanium detectors cooled by liquid nitrogen and surrounded by CsI and NaI anti-coincidence scintillation crystals. A graded z collimator limited the field of view to $3^\circ \times 8^\circ$ and a gondola pointing system provided 0.3° pointing accuracy.

A total of four flights were made with this instrument. Additional funding was obtained from NSF for the last three flights, which had primarily solar objectives. A detailed instrument description is given in section II. The main scientific results and the data analysis are discussed in section III, with current work and indications for future work summarized in section IV. A bibliography of publications resulting from this work is given in Appendix A. Appendix B consists of abstracts of talks given to the American Astronomical Society on this work.

A change of principal investigators was made after 1978-79, the first year of NSG-7592 and NSG-7527, from Professor Kinsey A. Anderson to Dr. Robert P. Lin.

This investigation was a collaborative effort involving investigators at the Space Sciences Laboratory and Lawrence Berkeley Laboratory at U. C., Berkeley; U. C., San Diego; and Centre d'Etude Spatiale des Rayonnements in Toulouse, France. Their names and addresses are listed below:

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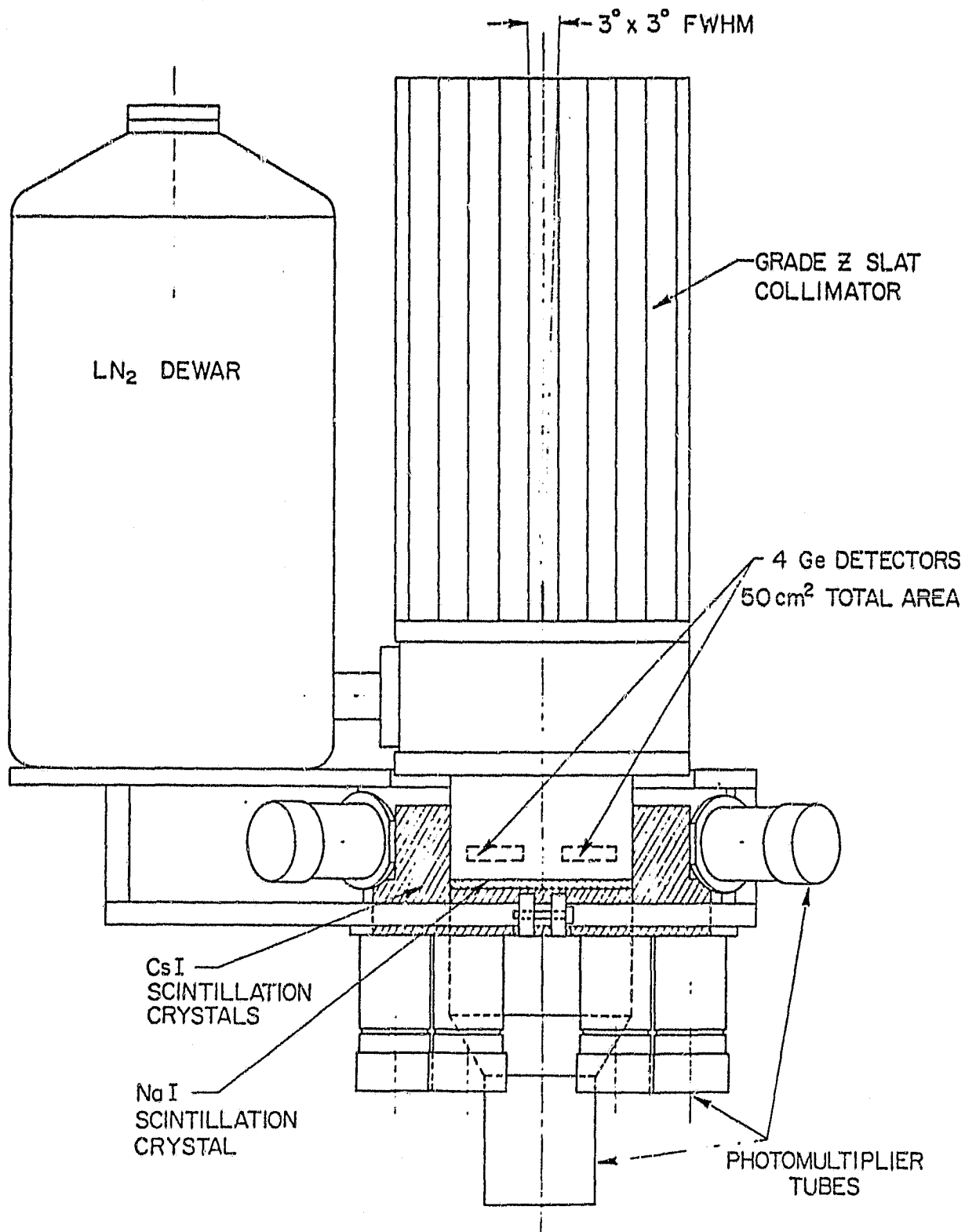
II. Instrument Description

In 1979 we began development of a high resolution instrument for hard X-ray spectroscopy. The instrument consists of an array of four ~ 4 cm diameter $\times$ 1.3 cm thick hyperpure planar germanium detectors, cooled by liquid nitrogen and housed within an aluminum vacuum cryostat (Figure 1). In turn this is surrounded by active anticoincidence scintillator shields. State of the art electronics, including cooled FET preamplifiers with pulsed charge feedback, were used to give an in-flight energy resolution of better than 1 keV FWHM (full width at half maximum) at 50 keV initially, improving to 600 eV on the last flight. These figures are the best achieved to date for astrophysical instrumentation. This instrument has been flown, along with a 300 cm² NaI/CsI phoswich scintillation hard X-ray detector, on two successful balloon flights from Palestine, Texas, one in October, 1979, the second in June, 1980. The scientific targets on the first flight were the Crab Nebula, the supernova remnant Cas A, and the Seyfert galaxy Markaryan 421. The primary target of the second flight was the Sun; several solar hard X-ray bursts, including one very intense flare, were observed. The Crab Nebula was also observed during this flight.

Two more flights were launched from Brazil in April and November, 1982. For these flights, a smaller gondola carrying only the germanium detectors without the 300 cm² phoswich scintillator was used. The active galaxy Cen A, the binary X-ray source GX 1+4, and the Galactic Center were observed in April, and the Sun in November. Improvements have been made to the instrument based on the experience gained from each flight.

Germanium Detectors

The detectors are fabricated from p type germanium; one face is an n^+ diffused lithium positive high voltage contact, while the other face is a p^+ boron implant signal contact. They are operated as reverse biased diodes with their

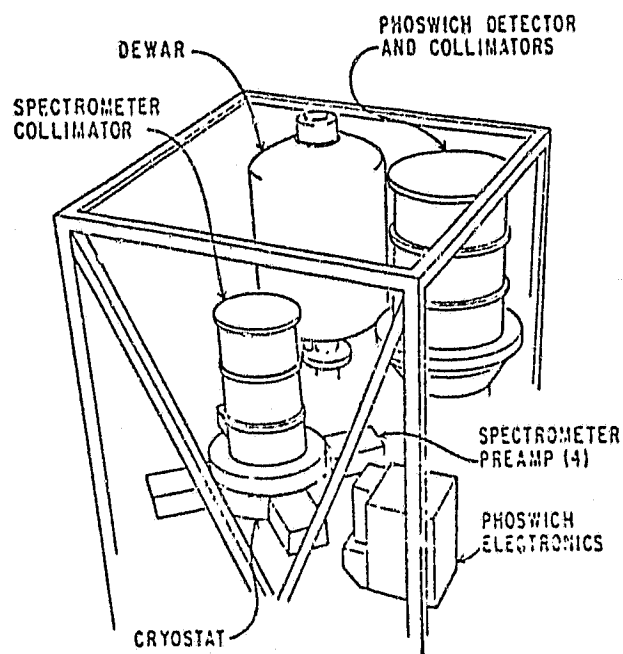


HIGH RESOLUTION X-RAY BALLOON INSTRUMENT

FIGURE 1a - Schematic of germanium detector system



FIGURE 1b - Instrument Module - The high resolution X-ray spectrometer and large area phoswich detector are co-aligned in a common elevation gimbal mounting. The two systems have identical collimation, 3° FWHM in elevation and 6° FWHM in azimuth. Observations are conducted using "elevation chopping" in which the source is tracked for one-half of the observing time and background accumulation is divided equally between a position 5 degrees above and below the source in elevation.



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volumes fully depleted of free carriers and with a field strength of ~ 1 kV/cm. The detectors are held in boron nitride cups with pressure-loaded indium pads (to make the electrical contact), and they are housed in separate aluminum modules for isolation. These sit within an aluminum vacuum cryostat, and are cooled to 95°K with liquid nitrogen. The liquid nitrogen coolant is kept at 12 p.s.i. over the ambient pressure by venting the boiloff gas through a relief valve. Photons enter through a 0.06" thick $\times$ 4.5" diameter beryllium window, and pass through 4 cm diameter holes in the cold plate to enter the detectors through their boron implant side.

Shields and Collimator

The active anticoincidence shield is a modification of a balloon-borne cosmic X-ray experiment designed, built, and flown by Space Sciences Laboratory and C. E. S. R. Toulouse [Hurley and Duprat, 1974; Anderson and Mahoney, 1974; Mahoney, 1974]. The active shield has three parts. The phoswich shield is a central 5 inch diameter $\times$ 1/4 inch thick NaI (Tl) scintillator optically coupled to a 5 inch diameter $\times$ 2 inch thick CsI (Na) scintillator; a single photomultiplier tube (PMT) views both. The annular shield, a 9 inch outer diameter $\times$ 2 1/4 inch long annulus of CsI (Na) viewed by 6 PMT's, surrounds the phoswich crystal. In front of these is the collimator shield with an 8 inch outer diameter and 5 inch inner diameter $\times$ 2 inch thick of CsI (Na) viewed by 4 PMT's. All of the shield lower level discriminators are set to ~ 30 keV. A shield event triggers a 14 μ sec logic signal used for anticoincidence.

Passive shields are used within the cryostat. These are 0.125 inch thick tantalum shields covered by 0.013 inch of molybdenum to prevent tantalum fluorescent X-rays from reaching the germanium detectors. Indium is used between the Ta cold plate shield and the detector modules to provide both good thermal contact and X-ray shielding. Surrounding the cryostat feedthrough

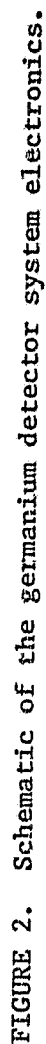
ring and directly above the active shields, there is an additional annular shield of 0.125 inch lead.

The graded z slat collimator is made from three 10.1 cm long sections, each consisting of eleven 0.7 mm thick plates, spaced by 1 cm. The plates are of 0.1 mm Ta, covered on both sides by 0.3 mm tin flashed with copper. The collimator walls are lined with 2 mm of lead. Two collimator sections are stacked to define a 2.6° FWHM elevation angle field of view (FOV), while a single orthogonal section defines the 5.2° FWHM cross-elevation angle FOV. The finite slat thickness reduces the on-axis transmission to 85%. Above about 300 keV, photons begin to leak through the collimator.

Detector Electronics

Each of the four germanium detectors has an independent signal chain, including a preamplifier, dual shaping amplifiers, pulse stretcher, active baseline restorer, and a 4096 channel pulse height analyzer (PHA). An electronic block diagram is shown in Figure 2. Each detector is D.C. coupled to a low noise, charge-sensitive preamplifier whose first stage is a Solitron 310 FET operating at $\sim 150^\circ\text{K}$ mounted within the detector module. A key element of the low noise electronics is the pulsed charge feedback reset system [Landis et al., 1982]. During reset, which occurs ~ 10 times a second, the signal processing electronics are disabled for $\sim 200 \mu\text{sec}$.

The output from the preamplifier goes into dual shaping amplifiers. The slow shaper-amplifier-discriminator ($\sim 10 \mu\text{sec}$ shaping time) converts the preamplifier signal into a unipolar pulse. The peak is detected and converted to a 12 bit PHA word by a run-down Wilkinson-type analog to digital converter for which a full scale event takes 1 millisecond. The fast shaper-amplifier-discriminator ($\sim 400 \text{ nsec}$ shaping time) gives fast pulses for detector-detector coincidence, pile-up rejection, timing, and rate accumulations. This dual



fast/slow amplifier system, together with the active baseline restorer, allows for single detector count rates in excess of 20,000 counts/second without spectral distortion.

The bias voltage for each germanium detector is supplied through one of four separate high voltage filter boxes, powered in pairs by two separately commandable (on/off only) high voltage supplies. Each detector also has a separately commandable pulse generator. Approximately every three hours during an observation, they are turned on for several minutes with a ~ 20 /second pulse rate for electronic calibration.

Digital Electronics

Each detector event is encoded into the telemetry stream in a 20 bit word, 12 bits for the PHA, 2 bits for the detector identification, 4 bits for fine timing to 0.5 millisecond, 1 bit for pair detector coincidence, and 1 bit for shield coincidence. Those Compton events which trigger two detectors set the pair detector coincidence bit. There are two commandable modes for detector shield anti-coincidence. In one mode, all detector events are analyzed and encoded with the shield coincidence bit either set or null. In the "shield veto enable" mode, the shield logic signal inhibits the PHA's from analyzing any shield coincident events. Polling logic queries each detector's signal ready flip-flop in turn for the next event to encode into the telemetry. The telemetry system can handle up to 500 total germanium detector events/second.

Scintillator events, fast rate scalars, slow rate scalars, and gondola status words are also transmitted. The 16 ten bit fast rate scalars, read out every 0.128 sec., accumulate separately each detector's valid event rate both in coincidence (4 rates) and in anti-coincidence (4 rates) with the active shields, the 3 anti-coincidence shields' rates, and the scintillator's rates over 5 energy ranges 22-33, 33-60, 60-120, 120-235, and >235 keV.

The slow rates, each read out every 8.192 seconds. include each germanium detector's live time and reset rate. During the time a signal chain is available, a 128 kHz crystal oscillator advances that detector's live time counter. The detector reset rates can be replaced by the pair detector coincidence rates on command.

For the last two flights this system was modified to accommodate only the germanium detectors, since the phoswich scintillator was not flown.

Burst Memory

A 650 Kbit burst memory was installed before the June 1980 flight to store the total germanium detector event rate and the 3 lowest energy scintillator rates. After automatically triggering on an elevated scintillator rate, the memory stores these four fast rates every 8 milliseconds, until the memory is half full, then for 32 msec until filled. This accumulates ~5 minutes of high time resolution rate data in 65,536 10 bit words. Then on command, the memory is read out in 65 seconds, replacing the normal germanium detector telemetry.

Before the 1982 flights this memory was enlarged to 2.6 megabits and modified to store Ge detector events rather than rates during a burst.

Tracking System

The gondola uses an alt-azimuth pointing system referenced to gravitational vertical and the local magnetic field direction. The balloon payload rotates beneath a field aligned magnetometer table to the target azimuth computed on the ground and sent up periodically by command. Concurrently, the thermally insulated instrument cage housing the germanium instrument and coaligned phoswich scintillator is rotated to the computed elevation angle. The pointing system automatically tracks a source in between ground commands, which are sent every 15 to 30 minutes.

A similar pointing system was used in the lightweight gondola for the 1982 flights.

III. Scientific Results

A total of four balloon flights were made with this instrument, the first two from Palestine, Texas, the last two from Uberaba and Cachoeira Paulista in Brazil. Data were obtained in all four flights from this instrument.

In the first flight on October 17-18, 1979, the Crab nebula (5 hrs), Cas A (3.5 hrs) and Mk 421 (3 ms) were observed. *Lin et al.* had reported an apparent cyclotron line feature from the Crab at 73 keV. We found no line emission at 73 keV (1 keV farther) with a 3σ upper limit of 1×10^{-3} ph/cm²sec. From the observation of the recent supernova remnant Cas A we obtained a 3σ upper limit of 1×10^{-3} ph/cm²sec for the combined 78.4 and 67.9 keV lines from the decay of Ti^{44} an isotope with 48 year half life predicted to be produced in nucleosynthesis.

The second flight on 27 June 1980 concentrated on the Sun (3 hrs). A large flare was observed at 1614 UT in which a new component of solar hard X-ray was discovered. This component was emission from a closely isothermal, very hot, $\sim 35 \times 10^6$ K plasma. The spectrum is so steep that it is unmeasurable by scintillation detectors [*Lin et al.*, 1981].

A second major discovery of this flight was that of solar hard X-ray microflares, hard X-ray bursts from the Sun too small to be associated with a flare or subflare. These occur at the rate of almost one per five minutes above a threshold of $\sim 7 \times 10^{-3}$ ph/cm²sec keV at 20 keV. The germanium detectors provided accurate energy spectra for the larger of these microflares. These showed that these bursts had power law, i.e., non-thermal, rather than thermal spectral shapes (see attached preprint, Appendix A).

This flight also showed that the Sun was not a source of 73 keV line emission. A 3σ upper limit of 1.5×10^{-3} ph/cm²sec observations, because of their instrument's wide field of view, was inconsistent with either the Crab or the Sun

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as the source of the 73 keV line.

Finally, an additional 2.5 hours' observation of the Crab again gave a negative result for the 73 keV line 3σ upper limit of 1×10^{-3} ph / cm² sec. The Crab data from the first two flights were later re-analyzed to look for a transient 73 keV line occurring only during the pulsed emission from the Crab pulsar. Such line emission was reported by *Strickman et al.* [1982]. No evidence for such a transient at 73 keV was present in these data.

For the third and fourth flights a lightweight gondola was used with smaller (11 million cu ft) balloons to facilitate launches from Brazil. Thus only the germanium detectors were flown. Because of unfavorable winds at dawn in Uberaba, the third flight was launched in the evening of April 19, 1982. One of the two-detector high voltage power supplies failed upon balloon ascent, leaving two germanium detectors (25 cm²) operating. As expected, the background in Brazil was about half of that in Texas. The cosmic sources observed were Cen A (3 hrs), GX 1+4 (5 hours), and the Galactic Center region (1 hr). Due to telemetry interference from a Brazilian TV station (radiating outside its assigned band) the data analysis has been slow and complex. No results are yet available.

The final flight was launched in the morning of November 24, 1982, from Cachoeira Paulista in Brazil, following several drenching rainstorms. The elevation drive jammed, so that only 40 minutes of solar data were obtained in the six hour flight. No large flare hard X-ray bursts were observed, but detailed data analysis has yet to be done.

IV. Current and Future Work

Mr. Richard Schwartz, a graduate student, is currently finishing his thesis on the results from this balloon instrument. The major part of his thesis deals with the large flare of 27 June 1980, both the new hot isothermal component and the non-thermal electron acceleration. He has found that there may be as many as three distinct electron acceleration phases in this flare. The data also provide, for the first time, hard X-ray spectra accurate enough to show that the > 30 keV emission can not be due to a single very high temperature thermal plasma.

The analysis of the solar hard X-ray microflares is just beginning. Comparisons with SMM and ground based data are needed to determine the origin and morphology of these tiny events. Further measurements are clearly needed to see whether these hard X-ray microflares generally accompany most, if not all, transient energy releases by the Sun.

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- Ling, J. C., Mahoney, W. A., Willett, J. B., and Jacobson, A. S., 1979, *Ap. J.* 231, 896.
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APPENDIX ABibliography of Publications Supported Wholly or in Part by NSG-7592

Bai, T., H. S. Hudson, R. M. Pelling, R. P. Lin, R. A. Schwartz and T. T. von Rosenvinge, First-order Fermi acceleration in solar flares as a mechanism for the second-step acceleration of prompt protons and relativistic electrons, Astrophys. J., 267, 433, 1983.

Lin, R. P., Solar flare energetics, in Gamma Ray Transients and Related Astrophysical Phenomena, AIP Conference Proc. No. 77, ed. by R. E. Lingenfelter et al., p. 419, American Institute of Physics, New York 1982.

Lin, R. P., R. A. Schwartz, R. M. Pelling and K. C. Hurley, A new component of hard X-rays in solar flares, Astrophys. J. Lett., 251, 109, 1981.

Lin, R. P., R. A. Schwartz, S. R. Kane, R. M. Pelling and K. C. Hurley, Solar hard X-ray microflares, submitted to Astrophys. J. Lett., 1983.

Schwartz, R. A., High resolution of hard X-ray spectra of solar and cosmic sources, Ph.D. Dissertation, Department of Physics, UC Berkeley, in preparation, 1983.

APPENDIX B

Abstracts of Talks Presented to the American Astronomical Society

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32.09.09 High Resolution Observation of the Crab Nebula, R. SCHWARTZ and R. P. LYN, U. Calif. Berkeley, SSL; R. PELLING, U. Calif. San Diego; and K. HURLEY, C.E.S.R., Toulouse, France - On a balloon flight from Palestine, Texas on October 17-18, 1979, we observed the Crab Nebula, Cas A, and Markaryan 421 with an x-ray spectrometer consisting of an actively shielded array of four liquid nitrogen coded planar germanium detectors with a total area of 50 cm². The spectral resolution was ~ 1 keV FWHM over the instrument's energy range of 30 - 200 keV. We find no evidence for line emission from the Crab over this range. In particular for the line feature at 73.3 ± 1 keV with intensity 3.8×10^{-3} photons/cm² sec (4 σ) previously reported by Lin et al., (1979); we obtain a 3 σ upper limit of 2×10^{-3} photons/cm² sec. With their best fit line width of 3.2 keV FWHM this feature, if present, should have been observed at 4.3 σ significance in our data.

June, 1980

University of Maryland

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Upper limits to the 68 and 78 keV Ti^{44}
line emission from the supernova remnant Cas A,
R. A. Schwartz, R. P. Lin, UCB, R. M. Pelling, UCSD.

The decay of Ti^{44} , produced during explosive nucleosynthesis, results in the emission of two low energy gamma ray lines of nearly equal strength at 78.4 keV and 67.9 keV. Using an array of four planar germanium detectors with a total area of 50 cm² and < 1 keV resolution, we observed the supernova remnant Cas A for four hours on Oct. 17-18, 1979, on a balloon flight from Palestine, Texas. For a line width < 1 KeV we obtain a 3 σ upper limit of 1×10^{-3} ph/cm² sec for each line.

January, 1981

Albuquerque, New Mexico

Observations of a Solar Hard X-ray Burst
with Very High Spectral and Temporal Resolution,
R. P. Lin, R. Schwartz, UC BERKELEY, M. Pelling, UCSD,
G. Hurford, CALTECH

In a balloon flight on June 27, 1980 we observed an intense solar flare x-ray burst at $\sim 1613-20$ U.T. with a 50 cm^2 array of four planar germanium detectors and a separate $\sim 300 \text{ cm}^2$ phoswich scintillation detector. These provided the best hard x-ray flare observations ever obtained in terms of energy resolution ($\sim 1 \text{ keV}$), time resolution ($\sim 8 \text{ ms}$) and sensitivity. We have discovered a new hard x-ray component occurring during the decay of the burst which is characterized by a very steep spectrum, $\frac{dJ}{dE} \propto E^{-11.2}$ between 20 and 40

keV with a significant excess above that energy. This component is too energetic to be an extension of the soft $10-20 \times 10^6 \text{ }^\circ\text{K}$ thermal spectrum. During the burst maximum the energy spectrum is observed to be very accurately power law between 20 and $> 200 \text{ keV}$, thus ruling out single or a few temperature thermal models. Finally the 10 GHz microwave intensity observed at Owens Valley on a 50 ms time scale appears to be related to the integral of the hard x-ray intensity, indicating that it is not produced by gyro-synchrotron emission but perhaps by bremsstrahlung from a very hot plasma produced by the energy loss of the hard x-ray electrons.

January, 1981 (Solar Physics Division)

Taos, New Mexico

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A search for line emission from the sun in the 20-200 keV energy range. R. Schwartz, R. P. Lin, UCSB, R. M. Pelling, UCSD.

Ling et al. have reported a line at 73.3 keV with intensity of 3.8×10^{-3} ph/cm² sec (4 σ) and a FWHM width ≤ 2.5 keV from the Crab Nebula. However, both the Sun and the Crab Nebula were in their field of view. The observed temporal variation of the line feature fits equally well to the transit of the Sun or of the Crab Nebula. On two separate flights of our high resolution (≈ 1 keV) four germanium detector array we observed the Crab without the Sun in our field of view. No line emission at 73.3 keV was detected to a 3 σ upper limit of 1×10^{-3} (cm² sec)⁻¹. Ling et al. suggests lead fluorescence as a possible source for the line emission.

We have also searched for line emission from the Sun. Our ₃ observation sets a 3 σ upper limit of 1.2×10^{-3} ph/cm² sec for narrow line emission at 73.3 keV. Also we will present the results of a search for quiet time continuum emission from the Sun.

References

1. Ling, J. C., Ap. J., 234, 753, 1979.

January, 1981 (Solar Physics Division)

Taos, New Mexico

Very High Spectral and Temporal Resolution
Observation of a Solar Hard X-ray Burst, R. Schwartz,
R. P. Lin, UC BERKELEY, M. Pelling, UC SAN DIEGO, K.
Hurley, CESR TOULOUSE

During a balloon flight on June 27, 1980 we observed an intense solar flare X-ray burst using a 50 cm² array of four planar germanium detectors and a separate 300 cm² phoswich scintillation detector. Using the narrow energy resolution of the germanium detector ($\lesssim 1$ keV from 15-200 keV) and the 128 msec. scintillator rate channels, we have made a detailed analysis of the hard X-ray flux during the impulsive phase (1614-1617:30 UT). The flare consists of a series of Elementary Flare Bursts (EFB), each with a FWHM of 3-13 seconds at around 100 keV. These bursts become broader at lower energies where the burst profiles merge into a smoother time profile. The EFB time profiles do not become narrower at energies above 100 keV. Also, there is a delay seen at the highest energies which is due to a second step acceleration mechanism. Additionally, 50-100 keV electrons are present throughout the decay phase (1618-1614 UT) and show both impulsive and gradual behavior.

June, 1983 (Solar Physics Division)

Pasadena, California