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THE PIONEER 10/11 AND HELIOS A/B COSMIC RAY INSTRUMENTS

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Summary

This paper describes the design and performance of a set of cosmic-ray particle experiments for the Pioneer 10/11 and Helios A/B space missions. These experiments had to be very light-weight, low-power and electronically sophisticated in order to meet the spacecraft and scientific requirements. Both sets of missions use several solid-state detector telescopes to measure protons from ∿100 KeV to ∿800 MeV and heavier ions up to Neon at ∿200 MeV per nucleon. Good performance is required for 7-8 years, and the system must tolerate large vibration loads and ionizing radiation doses up to $\sim 5 \times 10^5$ rads.

Introduction

The Pioneer 10 spacecraft was launched on March 3, 1972 on a direct flight to Jupiter where the encounter occurred on December 4, 1973. Pioneer 10 is now at a distance of ∿6 AU from the sun on a trajectory which will take it out of the solar system. Pioneer 11 was launched in April 1973, encountered Jupiter on December 3, 1974, and eventually will arrive at Saturn in 1979. Helios is a cooperative space mission with the Federal German Republic for a sophisticated solar probe going in to 0.3 AU from the Sun on two launches in December 1974 and late 1975. All these spacecraft contain similar experiments whose purpose is to carry out investigations of the energy spectra, charge composition and flow patterns of both solar and galactic cosmic rays. Additionally, the lowest energy telescope in this system has been designed to detect electrons and protons in the Jovian and Saturnian (if it exists) radiation belts.

Detectors

The detector systems in Pioneer and Helios are essentially identical. Three separate dE/dX vs. E telescopes, in combination, enable the following particle species and energy ranges to be measured: electrons, 50 KeV to ∿8 MeV; protons, 100 KeV to ∿800 MeV; alpha particles, to 600 MeV per nucleon; heavier elements up to Neon to ∿200 MeV/nucleon. In addition, the Helios experiment includes a proportional counter to monitor solar X-rays in the range 2-8 KeV.

Figure 1 shows a cross-sectional view of each of the three telescopes. The High-Energy Telescope (HET) at the left uses two thin detectors A and B to define an acceptance cone for incoming particles and to provide two separate measurements of dE/dX. The C_2 element consists of a stack of four identical detectors summed together. If a particle stops in C_2 (as determined by a $\overline{C}_3$ event) then C_2 measures its total energy. If it penetrates then C_2 and C_3 both provide dE/dX measurements.

The Low-Energy Telescopes (LET-I and -II) operate in a similar fashion, but LET-II uses significantly smaller, thinner detectors for lower energy particles and a smaller geometry factor. This detector was heavily shielded by lead and aluminum in the Pioneer instrument to reduce interference from gamma rays originating in the spacecraft radioisotope power supplies. Both LET-I and LET-II reject penetrating particles by using the rear elements (F and S_3) in anti-coincidence. LET-I uses D_1 and D_2 to define an acceptance cone for incoming particles and for a double dE/dX measurement, while LET-II uses a mechanical collimator instead. Particle events from HET and LET-I may be selected for pulse-height analysis.

Table I summarizes the characteristics of each of these telescopes and their component detectors.

TABLE I

Telescope	HET	LET-I	LET-II
Geometrical Factor (cm^2-ster)	.22	.155	.015
Detectors (thickness x area)	A,B: 2.5mm x $3cm^2$ C's: 2.5mm x $8.5cm^2$	D_1,D_2: 100μ x $1cm^2$ E,F: 2.5mm x $3cm^2$	S_1: 50μ x $50mm^2$ S_2: 2.5mm x $50mm^2$ S_2a: 2.5mm x $50mm^2$ S_3: 2.5mm x $200mm^2$

Pioneer carried one of each of these telescopes, Helios carries an additional LET-II, one directed 20° above the ecliptic and the other 20° below the ecliptic. The solar disc is thus 5° outside the field of view. Helios also includes a proportional counter with two active detector volumes within a common gas volume. Separate Be foil windows admit particles to be counted. A narrow collimator in front of one window is 1° wide in the ecliptic and ±10° above and below the ecliptic. This permits some sectoring of the solar disc when the spacecraft is near the sun. In front of the other window a second collimator, 60° wide, is covered with 2 mil aluminized mylar foil to eliminate low energy X-rays. This counter is sensitive only to penetrating charged particles, and is used for background correction.

Electronics

Pulses from each detector are amplified and shaped in a preamp/post-amplifier, and applied to one or more pulse-height discriminators which produce logic pulses of uniform amplitide and width for each input pulse exceeding the threshold. These logical pulses are used to form the many coincidence-anticoincidence conditions corresponding to various particle energies and types. Both single detector rates and coincidence rates are counted in 24-bit binary counters. Sixty-one such rates are monitored in the Pioneer instrument and 83 rates are monitored in Helios. The Pioneer rates are shown in Table II; Helios rate data includes additional LET-II rates and the 2-8 KeV X-ray rates. Certain coincidence conditions may initiate pulse-height analysis of selected events. The pulse ampli-

TABLE II

RATE	COINCIDENCE	PARTICLE/ENERGY
*R1	$(A_2K_1+A_1C_1)B\overline{C_3}$	Protons, $Z\geq2$: 20-56MeV/nuc
		Electrons: 2-8MeV
*R2	$A_1\overline{A_2}B\ C_3$	Protons: >230MeV
*	$A_1BK_2\overline{C_3}$	$Z\geq2$: 20-56MeV/nuc
*R3	$A_2B\ C_3$	Alphas: >56MeV/nuc
	$A_2BK_2\overline{C_1}$	Alphas: 20-30MeV/nuc
R4	$A_2BK_2C_1\overline{C_2}$	Alphas: 30-45MeV/nuc
	A_1	
R5	$A_2BK_2C_1C_2\overline{C_3}$	Alphas: 45-56MeV/nuc
	A_2	
R6	$A_1\overline{A_2}B\ \overline{C_1}$	Electrons: 2-4MeV
	$A_1\overline{A_2}B\ C_1\overline{C_2}$	Electrons: 4-6MeV
R7	$A_1\overline{A_2}B\ C_1C_2\overline{C_3}$	Electrons: 6-8MeV
	$A_2BK_1\overline{C_1}$	Protons, Alphas: 20-30MeV/nuc
R8	$A_2BK_1C_1\overline{C_2}$	Protons, Alphas: 30-45MeV/nuc
	$A_2BK_1C_1C_2\overline{C_3}$	Protons, Alphas: 45-56MeV/nuc
R9	B	
	C_1	
	C_2	
	C_3	
R10	D_{1_1} $\vdots$ D_{1_8}	
*R11	$D_1D_2\overline{F}$	Protons, $Z\geq2$: 3-21MeV/nuc
*	$D_1D_2\Sigma D\overline{F}$	$Z\geq2$: 3-21MeV/nuc
R12	$D_1D_2E_1\overline{F}$	Protons, $Z\geq2$: 6-21MeV/nuc
	$D_1D_2\Sigma DE_3\overline{F}$	$Z\geq2$: 6-21MeV/nuc
R13	$D_1D_2E_2\overline{F}$	Protons, $Z\geq2$: 10-21MeV/nuc
	$D_1D_2\Sigma DE_4\overline{F}$	$Z\geq2$: 10-21MeV/nuc

RATE	COINCIDENCE	PARTICLE/ENERGY
R14	D_1	
	D_2	
	E_1	
	F	
	S_1	
	S_2	
	S_3	
	S_{2a}	
R15	$S_{1_1}\ \overline{S_2}\ \overline{S_{2a}}\ \overline{S_3}$	Protons: .15-2.1MeV
	$S_{1_2}\ \overline{S_2}\ \overline{S_{2a}}\ \overline{S_3}$	Protons: .72-2.1MeV
	$S_{1_3}\ \overline{S_2}\ \overline{S_{2a}}\ \overline{S_3}$	Protons: 1.2-2.1MeV
	$S_{1_4}\ \overline{S_2}\ \overline{S_{2a}}\ \overline{S_3}$	Alphas: .6-2.1MeV/nuc
R16	$S_1\ S_{2_1}\ \overline{S_{2a}}\ \overline{S_3}$	Protons: 3.1-21MeV
	$S_1\ S_{2_2}\ \overline{S_{2a}}\ \overline{S_3}$	Protons: 5.7-21MeV
	$S_1\ S_{2_3}\ \overline{S_{2a}}\ \overline{S_3}$	Protons: 15.1-21.2MeV
	$S_1\ S_{2_4}\ \overline{S_{2a}}\ \overline{S_3}$	Alphas: 6-21.2MeV/nuc
SR1	$A_1\overline{A_2}B\ C_1\overline{C_3}$	Electrons: 4-8MeV
	$A_2BK_1\overline{C_3}$	Protons, $Z\geq2$: 20-56MeV/nuc
	$D_1D_2\overline{F}$	Protons, $Z\geq2$: 3-21MeV/nuc
	$D_1D_2E_1\overline{F}$	Protons, $Z\geq2$: 6-21MeV/nuc
SR2	$S_{1_5}\ \overline{S_2}\ \overline{S_{2a}}\ \overline{S_3}$	Protons: .12-2.1MeV
	$S_{1_6}\ \overline{S_2}\ \overline{S_{2a}}\ \overline{S_3}$	Protons: .52-2.1MeV
	$S_{1_7}\ \overline{S_2}\ \overline{S_{2a}}\ \overline{S_3}$	Protons: 1.1-2.1MeV
	$S_{1_8}\ \overline{S_2}\ \overline{S_{2a}}\ \overline{S_3}$	Protons: 1.5-2.1MeV
	$\overline{S_1}\ S_{2_5}\ \overline{S_{2a}}\ \overline{S_3}$	Electrons: .12-2MeV
	$\overline{S_1}\ S_{2_6}\ \overline{S_{2a}}\ \overline{S_3}$	Electrons: .40-2MeV
	$\overline{S_1}\ S_{2_7}\ \overline{S_{2a}}\ \overline{S_3}$	Electrons: .68-2MeV
	$\overline{S_1}\ S_{2_8}\ \overline{S_{2a}}\ \overline{S_3}$	Electrons: .97-2MeV

NOTES: $K_1 = A+B + 1.8(C_1+C_2)$.
$\Sigma D = D_1+D_2 + 1.6E$.
* designates PHA conditions.
Rates R15, R16, Sr2 and R14e-R14h appear twice in the Helios instrument.

tudes of three selected detector outputs are digitized by three 10-bit ADC's.

Linear Circuits

The pulse-height analyzer and coincidence system electronics for the Pioneer and Helios missions were accomplished using nearly identical designs. The same building blocks contained in Pioneer were used, with only slight modification, in the Helios systems. Each experiment contained three mechanically and electrically separate subsystems, one for each telescope. Since Helios contains two identical LET-II's, this subsystem is exactly double its Pioneer counterpart.

The preamps use an FET input in a conventional cascade configuration. After shaping with single integration and differentiation time constants of 0.6 μSec, the pulses are differentially coupled to noise-cancelling linear buffers to eliminate common mode noise pickup. CMRR was measured to be ∿50 db at the frequencies of interest.

Each of the HET, LET-I and LET-II subsystems operates in a similar fashion. Figure 2 shows the HET system. Each noise cancelling buffer is followed by another buffer to boost the incoming signal to a level suitable for pulse-height discrimination. The nominal low-level signal to be discriminated corresponds to Channel 1 of the PHA, or 5 millivolts. These low-level discriminators are stable with ±0.5% total drift from -20°C to +40°C. A lower power version of discriminator is also used where ±2% stability is tolerable. Three of eight discriminators in HET are of this variety.

Two linear summing amplifiers are used in HET. The first linearly adds the C_1 and C_2 buffered inputs. This sum is presented to the PHA for analysis under the proper conditions, and hence must exceed the linearity requirements of the PHA. The second summing amplifier adds the signals A and B with a weighted output from the first summing amplifier, $[A + B + 1.8(C_1+C_2)]$. This signal is fed into two discriminators for use in the coincidence logic to separate protons from electrons, and to separate $Z \geq 2$ particles from protons.

In the HET system there are 15 basic coincidence equations, none of which have less than 5 terms. Six additional singles rates are produced. These are multiplexed into the 10 rate outputs. Four of the coincidence conditions are used in the PHA control logic. Inputs to these equations are both pulse and level. The pulse inputs are derived from the discriminators while the levels are derived from the data system to control commutation of the rates.

To insure that coincidence timing is not affected by "discriminator walk" when two pulse inputs are coincident, an active delay has been incorporated. Since the B input appears in all multi-pulse equations, it is delayed 1.5 microseconds using a monostable circuit. The remaining 7 discriminators are followed by 3.0 microsecond monostables. The delayed edge of the B monostable is fed to an edge-coupled high-speed gate, whose other "anding" inputs are 3.0 microsecond-wide pulses or levels. This method insures that if all inputs are coincident within 1.5 microseconds, the proper equation timing will be fulfilled.

The coincidence system also selects events for pulse-height analysis. There are four coincidence conditions which can initiate analysis; two contain the term C_3 (penetrating particles) in which case B_1 $(C_1 + C_2)$, and $\underline{C_3}$ are analyzed. The other two conditions contain $\overline{C_3}$ (stopping particles) for which A, B and $(C_1 + C_2)$ are analyzed. Priority selection of event types allows higher priority events to be analyzed and stored in place of lower priority events. The relative priority of the four event types is rotated so that each type has highest priority for one-fourth the time. This emphasizes the occurrence of relatively rare events in the data.

The pulse-height analyzer system contains four delay lines and linear gates, three height-to-time converters, a gated current source and a gated clock. When an acceptable event has occurred, "open" signals are sent to the proper linear gates (B, $[C_1 + C_2]$ and A or C_3). The input signals are delayed 3.5 microseconds to compensate for delays in the coincidence and priority logic matrices.

The HTC is of the Wilkinson discharge type, the usual choice for nuclear spectrometers because of its excellent differential linearity characteristics. The gated constant current source remains on between events and is turned off slightly after opening of the linear gate. This minimizes the effect of noise spikes associated with opening of the linear gate, and improved the low-channel resolution and linearity significantly. The PHA's are able to resolve Channel 1 (5 millivolts) and produce a total differential nonlinearity of ±1.5% over the top 99% of full scale (5 volts or Channel 1024). The digitizing clock is 500 KHz, providing a 2-millisecond conversion time for full-scale inputs. The three 1024 channel PHA's used in HET require less than 30 milliwatts of power.

The PHA system outputs three gated pulse trains which are counted in binary counters. Additional tag bits are stored with each three-parameter PHA quantity which identifies the event type, priority, sector ID of spacecraft spin, and a C_2 range indicator to further characterize each event.

The LET-I and II systems shown in Figures 3 and 4 operate very similarly to HET. The linear buffers, discriminators and coincidence matrix use the same circuits as in HET. LET-I PHA data contains digitized values of the D_1, D_2, and E detector pulses, and tag bits provide sector ID, priority and event type information. A two-level priority system is used, and both event types are allotted equal time as highest priority events. The coincidence rates detected by LET-I and LET-II are also listed in Table II.

The PHA and coincidence systems were fabricated using a mother board/daughter board technique. Each functional module (i.e. buffer, monostable, linear gate, etc.) is fabricated on .6" x 1.2" thick film wafers or printed circuit cards. Module leads are soldered to miniature bifurcated terminals on the mother board. This provides excellent serviceability since any module may be easily removed. It also provides excellent packing density since the modules are spaced on 0.1 inch centers. The Pioneer and Helios experiments each contain approximately 300 such modules in the PHA-coincidence systems.

Data Systems

All rate data is counted in "Mars bugs," a custom PMOS LSI chip developed at GSFC.[1] A single chip contains a 24-bit binary counter, a quasi-log compressor to convert the 24-bit binary number to a 5-bit characteristic and a 7-bit mantissa, and a 12-bit storage buffer to hold the data for readout. PHA data is also counted and stored in PMOS IC's. The Pioneer and Helios PMOS data systems are quite similar in design. All S/C interface, command processing logic, control of the accumulation intervals, and formatting of Rate and PHA data into the available telemetry space is accomplished in a spacecraft-unique Interface Data System (IDS) using low-power T^2L circuits. Discreet components were used where necessary to comply with S/C interface impedances and levels.

The telemetry formating was designed to keep the rate data cycle time between 3 and 7 minutes for as many bit rates and formats as possible which were most likely to be used during a nominal mission, or not more than one-half of the science telemetry available to each experiment. PHA data is interleaved with rate data, and can process up to 3 events/sec on Pioneer, or 5 events/sec on Helios at the highest available bit rates. PHA telemetry is always equally divided between HET and LET. Because of the wide variation in bit rate (2048/sec to 16/sec on Pioneer, 4096/sec to 8/sec on Helios), a complete data cycle for all rates becomes quite long, up to ∿1.7 hours on Pioneer and ∿2.5 hours on Helios at the slowest possible combination of bit rate and format.

Both experiments acquire spin-sectored data. A sectored rate synchronizer generates suitable control signals to insure that the sectored rate accumulators are live for an exact integral number of spacecraft revolutions. The number of revolutions is determined by the bit rate in use and varies from 1 rev/readout to 31 revs/readout on Pioneer (spin rate ∿5 RPM), and between 53 revs/readout to 2231 revs/readout on Helios (spin rate ∿60 RPM). Sectors are 45° wide on both spacecraft. The Helios instrument also contains a separate X-ray sectoring system which counts solar X-rays in eight very narrow sectors centered on the solar disc. Since it would have been quite difficult to accurately align the X-ray sensor on the spacecraft, the X-ray sector synchronizer provides for a variable electronic delay between the "see sun" pulse from the solar aspect sensor and the beginning of X-ray live time. This can be adjusted by ±3.2° about the nominal orientation in 31 steps by ground command. The output of the narrow-angle X-ray detector is then multiplexed sequentially to eight accumulators, each receiving counts for about 10.5' of arc. These window widths can be doubled to 21' of arc by command when the S/C is inside ∿.5 AU.

Commandable features include: a) disabling the sector synchronizers in the event of failure, b) turning on internally-generated test pulses to stimulate the electronics for pre-flight and in-flight checkout, c) disabling the 1700-volt power supply for the X-ray counter (Helios only), and d) enabling a self-check system for the commandable X-ray offset (also Helios only).

Conclusions

This hardware is an example of an extremely lightweight, low-power electronic design for severe environmental conditions. The experiment qualified in vibration at 40 g's and was subjected to almost 5 x 10^5 rads in Jovian radiation belts. It has already been operating in flight for 2.8 years, and we expect to be able to receive data from Pioneer 10 for another 4-5 years. Weight was a major problem, especially on Pioneer. The experiment weighed 2.2 kilograms for the sensor systems, the electronics system consisting of the charge-sensitive preamplifers, shaping amplifiers, thresholds and logic circuitry, priority control system, six 10-bit pulse-height analyzers, an extensive data system and the low-voltage and detector bias dc-dc converters. Power consumption was 2.4 watts. The Pioneer experiment includes more than 8,000 discrete electronic components per system and more than 40,000 transistors - largely in medium and large-scale integrated circuits.

Experiment performance has been excellent. Figure 5 shows the LET PHA data for the August 1972 event. This is a plot of the average dE/dX value ($[D_1 + D_2]/2$) vs. the E value with a consistency check applied to the D_1 and D_2 values. The chemical elements are readily identified, and isotopic separation even for the Magnesium line is possible.

Acknowledgements

Much of the design and fabrication was accomplished at Spacetac, Inc., Bedford, Mass. We gratefully acknowledge the efforts of P. Monteforte and R. Messier for the layout and assembly of the instruments, and D. Deltano and R. Jehu for subsystem testing. Power converters were designed and tested by D. Schute, B. Hurowitz and R. Hayes.

At GSFC the detector telescopes were carefully assembled and tested by W.D. Davis; final system assembly, testing, and calibration was performed by M. Beazley. Mechanical design was provided by H. Trexel. To all we extend our thanks for their assistance and patience.

Reference

1. H.O. White, Jr., and D.C. Lokerson, "The Evolution of IMP Spacecraft MOSFET Data Systems," IEEE Trans. Nuc. Sci. NS-18, No. 1, 233 (1971).

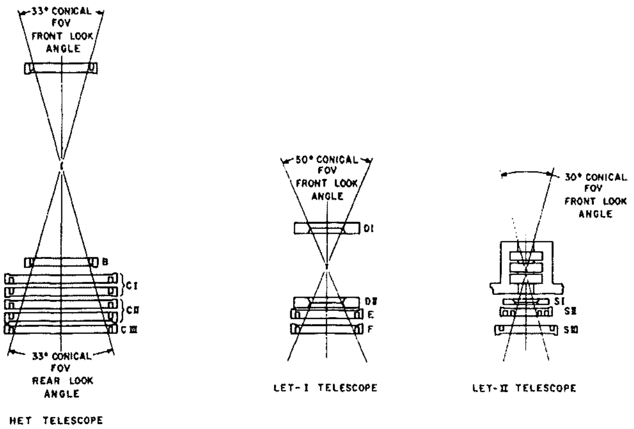

Figure 1. HET, LET-I and LET-II Telescope Assemblies.

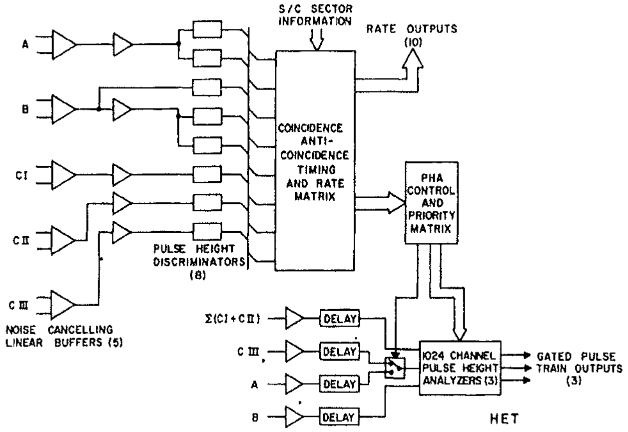

Figure 2. HET Block Diagram.

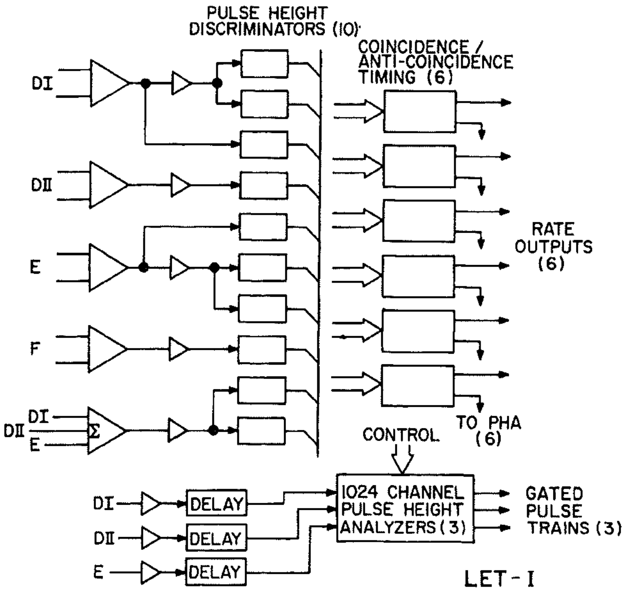

Figure 3. LET-I Block Diagram.

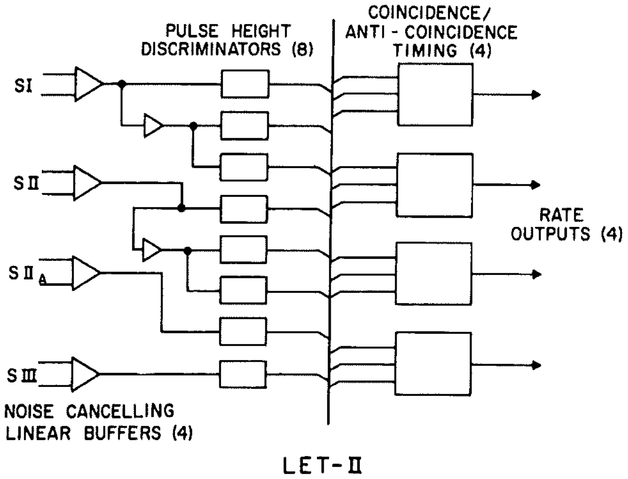

Figure 4. LET-II Block Diagram.

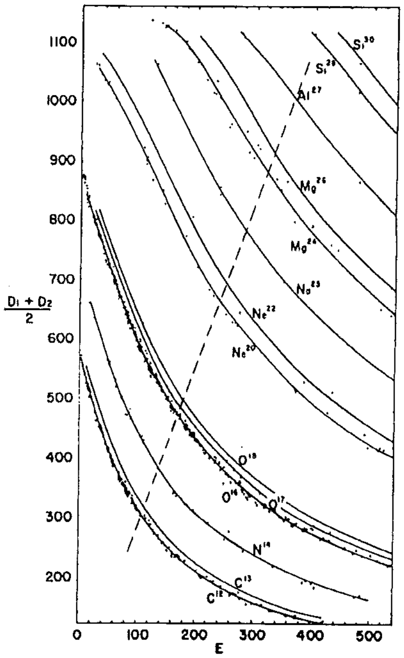

Figure 5. dE/dX vs. E results from the Pioneer LET-I telescope during the August 1972 solar event. Clear isotopic resolution for elements up to Mg. is possible.