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SPACEBORNE ENERGETIC PARTICLE INSTRUMENTATION

This article describes three APL-built particle instruments that are intended to characterize energetic ions and electrons in space under widely varying conditions. They measure particle masses, energies, and fluxes. The unique design features of each instrument, as well as the general engineering techniques, are discussed.

INTRODUCTION

The primary thrust of the APL space research program is to develop an understanding of the behavior and ultimate sources of the magnetic and electric fields, plasmas, and energetic particles that permeate the cosmos. We now know, for example, that the solar wind—a fully ionized hydrogen gas moving outward from the sun through the solar system at speeds of many hundreds of kilometers per second—interacts with planetary magnetic fields to form the planetary magnetosphere high-altitude environments that extend to great distances from the parent bodies and that are populated by plasmas of varying densities, temperatures, and bulk velocities. In fact, magnetospheres have become a common feature throughout the universe, having been observed around several planets and a variety of astrophysical objects.

Observations from in situ instruments are required in order to advance our understanding of space plasma phenomena. The design of the instruments (for sensitivity, angular resolution, time resolution, etc.) is dictated by both the expected characteristics of the plasma regions being investigated and by the available spacecraft resources (weight, power, telemetry rate, etc.). We describe here three examples of recent state-of-the-art charged particle instruments built at APL to investigate three distinctly different solar system plasma regimes: the interplanetary medium over the poles of the sun, and the magnetospheres of Jupiter and of the earth. The instruments share much commonality in their design owing to similar engineering constraints and scientific goals. They represent our continuing capability to identify and measure charged particles over a wide energy range throughout the solar system.

GENERAL DESIGN APPROACH

In many ways, the design of a particle instrument is similar to that of a complete spacecraft. In addition to collecting particle data, the instrument must also perform a number of maintenance and communications functions, including thermal control, power regulation, instrument housekeeping, command process-

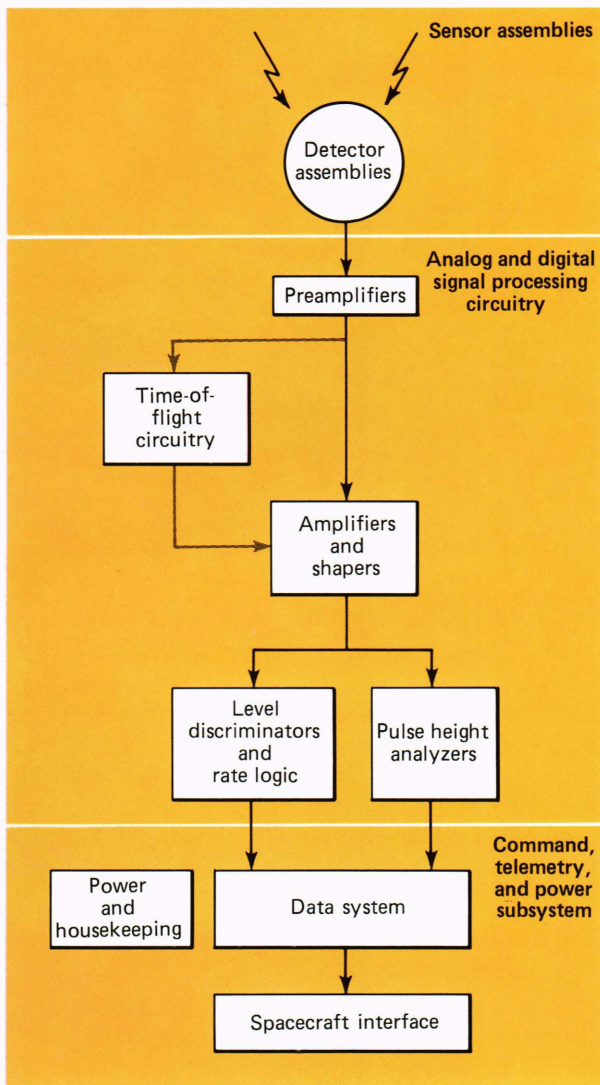<div style="background:pink">

GLOSSARY OF ACRONYMS

AMPTE—Active Magnetospheric Particle Tracer Explorers
CMS—Composition Measurement Subsystem
EPD—Energetic Particle Detector
HI-SCALE—Heliosphere Instrument for Spectra, Composition, and Anisotropy at Low Energies
LEFS—Low Energy Foil Spectrometer
LEMS—Low Energy Magnetic Spectrometer
MEPA—Medium Energy Particle Analyzer
RAM—Random access memory
ROM—Read-only memory

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ing, and telemetry formatting. Unlike a self-contained spacecraft, however, no power generation or radio communications equipment is required; these functions are provided by the host spacecraft bus.

The amount of circuitry required for a typical mission can be significant and, as with many space missions, the power and mass limitations are often severe. Equally significant is the need for high radiation tolerance by all components used in the spacecraft. The need for low-power, densely packed, radiation-hardened circuitry leads to extensive use of custom integrated circuit packaging techniques within the design.

The overall design can be divided into three subsystems (Fig. 1): the sensor assemblies; the analog and digital signal processing circuitry; and the command, telemetry, and power subsystem. Each will be discussed briefly.

Energetic ions and electrons are usually detected by measuring their interactions with a solid-state silicon detector (see the first boxed insert). The detectors may be from 2 to several thousand micrometers thick, depending on what particles and energies are of interest and whether the detector is to stop the particle or simply to measure its passing. As particles interact with the detectors, they lose energy to the silicon material, and the loss is translated into a fast current pulse.
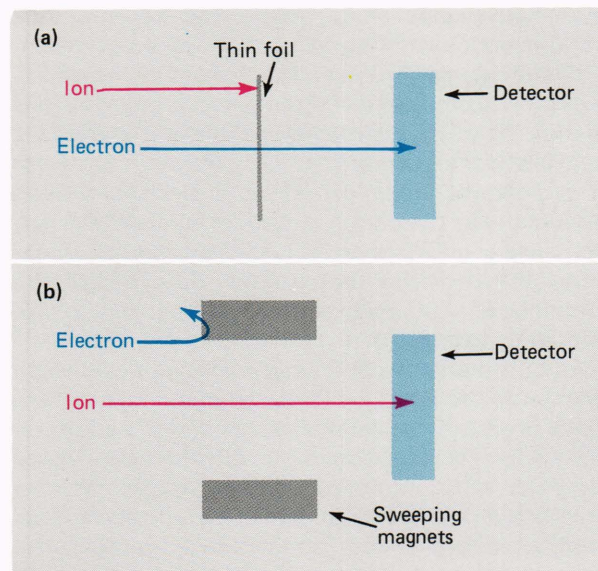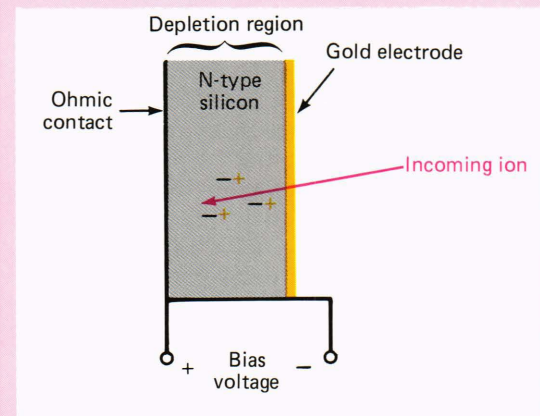
Figure 1—General block diagram of a particle detector instrument.

A solid-state silicon detector is a thin solid disk of silicon with two electrodes attached to it. The gold electrode forms a diode junction with the N-type silicon material. Properly reverse-biasing the junction diode will deplete the silicon of almost all mobile charge carriers; thus no current flows. When an energetic particle strikes the detector, it interacts with the silicon lattice structure, creating electron-hole pairs. Before they can recombine, these newly formed charge carriers are quickly swept toward the opposing electrodes. The liberated charge is collected as a current pulse with an integrated amplitude proportional to the energy that the incident particle lost in the detector.

Detecting the surrounding energetic plasma is a fairly straightforward task. Selectively measuring a given particle species' energy, rate, and directional characteristics is more difficult. It is not uncommon to want to measure events that comprise less than 1 part in a million of the surrounding energetic plasma. Several techniques are used to sort the incoming energetic stream for particles of interest, while eliminating or ignoring the rest. The physical designs of both the sensor assembly and the electronic circuit play important roles.

The best way to avoid processing unwanted particles is to prevent them from striking the detectors by using magnetic and/or electrostatic fields to selectively deflect the charged particles (Fig. 2) and by absorber materials both around and between detectors.

Stacking detectors behind one another can produce a measurement of the particle energy, mass, and velocity based on knowing the energy absorption properties of the detectors and measuring the transit time of the particle between detectors.

Figure 2—Two techniques for separating ions and electrons. Figure 2a shows how a thin (approximately 2 micrometer) aluminized parylene foil passes electrons (greater than 30 kiloelectronvolts) and stops low-energy ions from hitting the detector. Figure 2b shows how the opposite effect is achieved; the strong sweeping magnets deflect electrons while passing ions to the detector.

This technique can also be used to discriminate among particles of interest. For example, note that detectors 1 and 2 in Fig. 3 are intended primarily to measure electrons, whereas detector 3 measures ions. Such a telescope might also use absorber materials to allow measurements of higher energy ions. Because of the wide range of different particles and energies present, several detector types and configurations might be used on a single instrument. Several telescopes of similar design, each with a different aperture size or orientation, may also be used to provide greater spatial coverage and instrument flexibility.

Signals from the detectors are input to charge-sensitive preamplifier circuitry. The outputs may be processed further for timing information (see the discussion of time of flight below) or may be sent directly to additional amplifier and shaping stages.

The energy deposited in the detectors, as linearly represented by analog signal amplitudes, can now be determined. A low-resolution measurement is made by using several level-discriminators on each channel. Combinatorial logic then monitors which discriminators were activated and assigns the particle event to one of several energy bins, called rate channels. The number of events falling in each rate channel stored in a binary counter (typically 24 bits), called an accumulator, is read out periodically by the instrument data system.

A higher resolution energy measurement of the analog signals can be made by using a pulse height analyzer circuit, which produces a multichannel (typically 32 to 256 bins) energy spectrum that covers part or all of the rate channel energy range. The spectrum data are also periodically transferred to the data system.

To provide an absolute measurement of the stability of the detector and analog circuitry through the long mission life of the instrument, calibration sources are included in the instruments. They may take the form of radioactive alpha particle and electron sources mounted near the detectors and/or internally generated analog pulses injected into the amplifier chain. Data generated from these sources during flight can be compared with previously recorded test data to provide an assessment of overall instrument health.

All information from the rate logic and pulse height analyzer is processed by the instrument data system, which is part of the command, telemetry, and power subsystem. The data system is a microprocessor-based computer with on-board random access memory (RAM) and read-only memory (ROM). It processes incoming commands and formats the outgoing instrument telemetry stream via the spacecraft interface, monitors various operational parameters in the instrument (voltages, temperatures, etc.), and initiates alarm routines if a problem is detected. In-flight reprogramming of the operating software is accomplished by using ground-commanded "software patches" in place of normal program blocks.

This type of advanced control system, now becoming standard in most space instrumentation, provides a great deal of instrument flexibility and control and
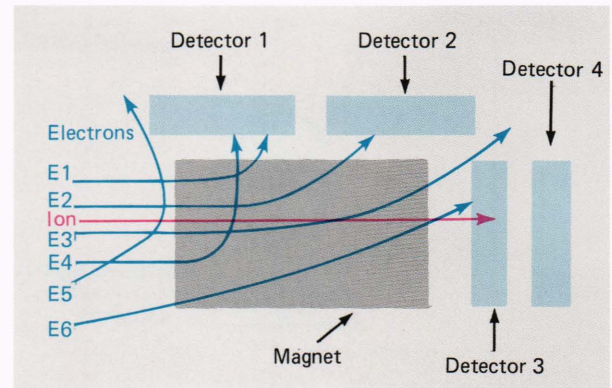
Figure 3—The incoming particle stream is sorted magnetically according to particle type, energy, and direction. Electrons E1, E2, and E4 are deflected to electron detectors 1 and 2. Electrons E3 and E5, having too high an energy and the wrong direction, respectively, are swept away from the detectors. The ion strikes detector 3 (ion detector) undeflected. Note that the higher energy electron E6 also strikes detector 3; this is an unwanted background count and must be sorted out in the electronics. Detector 4 can be used in an anticoincidence mode with detector 3 to reduce high-energy penetrator counts.

allows increasingly sophisticated on-board processing of data. Both features are highly desirable on deep space probes, where low telemetry rates and autonomous operations are necessary.

We will now describe the unique features of the three instruments (Figs. 4a, 4b, and 4c), synopses of which are presented in Table 1.
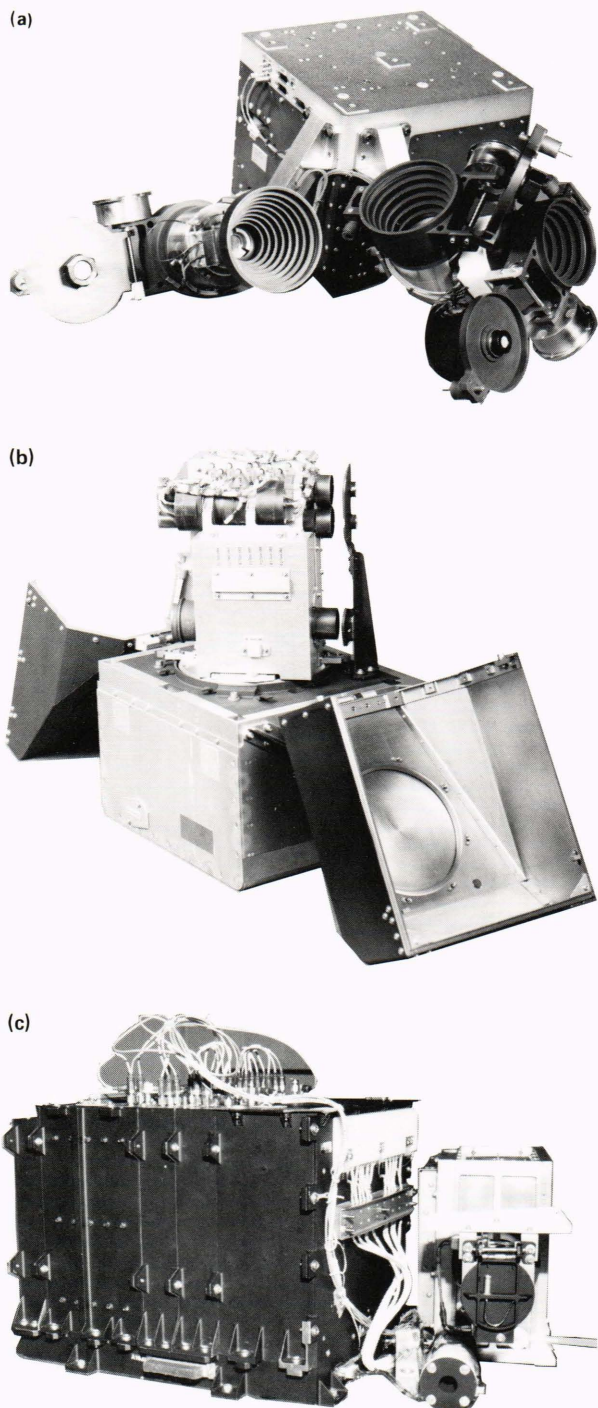
SOLAR POLAR HI-SCALE INSTRUMENT

The Heliosphere Instrument for Spectra, Composition, and Anisotropy at Low Energies (HI-SCALE) (Fig. 4a) will measure interplanetary particle distributions on the International Solar Polar Mission (recently renamed Project Ulysses), which is scheduled for launch in May 1986.[1] The spacecraft will pass over the poles of the sun during the period 1988-91.

HI-SCALE uses three distinct silicon solid-state detector systems: the Low Energy Magnetic Spectrometer (LEMS), the Low Energy Foil Spectrometer (LEFS), and the Composition Aperture. The first two provide pulse-height-analyzed single-detector measurements in the energy range of 0.05 to 5.0 megaelectronvolts. The latter system uses a multiparameter detection technique, $\Delta E \times E$ (Fig. 5), to measure ion composition in an energy range of 0.2 to 15.0 megaelectronvolts per nucleon from protons to iron ions.

Both systems also use a technique called anticoincidence testing to reduce further the invalid event processing. A "shadow" detector measures unwanted penetrating particles, and its resulting output inhibits processing in the other detector channels.

Data taken with the LEMS/LEFS detector assemblies are processed into a 32-bin energy spectrum using a novel hardware spectrum accumulator. The circuit, which uses a RAM to store counts and a ROM-based binary incrementor can sort and store spectral data at rates greater than 25,000 events per second.

(a)

(b)

(c)

Figure 4—(a) HI-SCALE instrument for the International Solar Polar Mission, (b) EPD instrument for the Galileo orbiter spacecraft, and (c) MEPA instrument for AMPTE.

Separate energy spectra are accumulated over each of four or eight angular sectors for each of the four LEMS/LEFS detectors.

Nearly full spherical coverage is provided every spacecraft spin (12 seconds) by using five separate apertures, each with a different inclination with respect to the spacecraft spin axis. The detector assemblies, using both the absorber technique and magnetic deflection to differentiate between incoming particle types

(a)

(b)
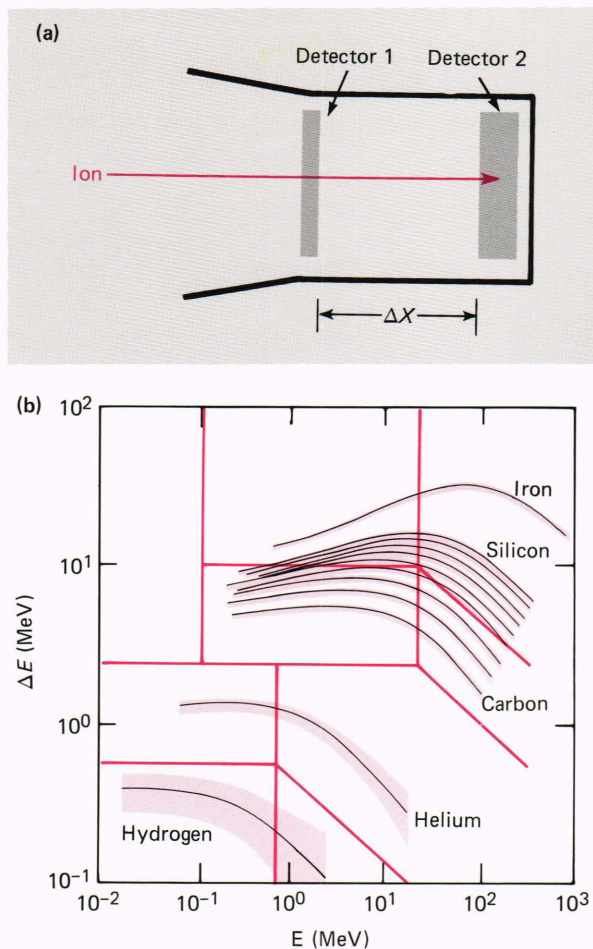
Figure 5—(a) The ion strikes the front detector in the composition measurement telescope, passes through it, and travels the distance ΔX to detector 2, where it is stopped. A small amount of the initial particle energy, ΔE, is deposited in the front detector; the remainder, E, is deposited in the back detector. Plotting the measured ΔE versus E produces particle tracks that can be separated by energy and species. (b) Predicted particle energy loss in megaelectronvolts (MeV) in a Solar Polar telescope for a number of elements over a range of incident energies. The red lines are rate channel boundaries.

(Fig. 2), have large geometric factors (up to 0.48 square centimeter-steradian) to permit operation in low flux regions. Thin aluminized plastic foils (approximately 2 micrometers thick) are used to pass electrons while excluding ions in some apertures. In contrast, strong sweeping magnets exclude electrons while passing ions in other apertures. Radioactive calibration sources are mounted on aperture covers that can be opened and closed on command by means of thermal motors.

Magnetically deflected electron calibration data taken with the LEMS 30 telescope at the Goddard Space Flight Center are shown in Fig. 6, along with a computer simulation of the electron trajectories.

GALILEO ENERGETIC PARTICLE DETECTOR INSTRUMENT

The Energetic Particle Detector (EPD) instrument (Fig. 4b) will measure the interplanetary and Jovian

Table 1—Instrument characteristics for HI-SCALE, EPD, and MEPA.

Features	*HI-SCALE*	*EPD*	*MEPA*
Region of solar system	Interplanetary over poles of the sun	Magnetosphere of Jupiter	Magnetosphere of earth
Mass (kilograms)	5.775	10.23	12.4
Size (maximum outline dimensions) (millimeters)	330 × 360 × 225	451 × 198 × 506	235 × 305 × 193 (electronics) 96 × 282 × 184 (telescopes)
Nominal power usage:			
Instrument (watts)	4.0	7.7	17.9
Heaters (watts)	7.5	3.5 (10.3 maximum)	—
Launch date	May 1986 (expected)	May 1986 (expected)	August 16, 1984
Telemetry rate (bits per second)	160 (maximum*)	912	735
Telescope apertures	5	7	2
Detectors	7	17	4 (including two foils)
Telescope geometry range (square centimeter-steradians)	0.05-0.48	0.005-0.5	0.001-0.01
Spatial coverage	Approximately full spherical every 6 seconds	Full spherical every 140 seconds	Angular distribution in one plane every 6 to 24 seconds
Energy coverage:			
Ion composition (megaelectronvolts per nucleon)	0.2 to ≥15.0	0.08 to ≥10.0	≥0.01 to 6.0
Ion energy, $z \geq 1$ (megaelectronvolts)	0.50 to 5.0	0.02 to 55.0	0.02 to 6.0
Electron energy (megaelectronvolts)	0.030 to 0.3	0.015 to ≥11.0	—

*Adjusted according to spacecraft telemetry rate.

magnetospheric particle distributions on the Galileo orbiter spacecraft, which is scheduled for launch in May 1986. On its approach to Jupiter, the spacecraft will release a probe into the atmosphere. The remainder of the spacecraft, of which the EPD is a part, will then orbit Jupiter 11 times over the next 20 months, passing very close to the large Jovian moons. The EPD will measure the dynamics and composition of the hot plasmas trapped in the huge planetary magnetosphere and their interaction with the Jovian moons.

The EPD uses two distinct silicon solid-state detector systems: the Low Energy Magnetic Measurement System and the Composition Measurement Subsystem (CMS). The former uses magnetic focusing to make pulse-height-analyzed single-detector measurements of ions and electrons (Fig. 3). Anticoincidence detectors are used to reject high-energy penetrating particles from analysis. The CMS uses a multiparameter detection technique (Fig. 5) to measure ion composition in an energy range from 0.08 to 10 megaelectronvolts per nucleon for ions from protons to iron. In addition to the $\Delta E \times E$ information, as produced in HI-SCALE, the CMS also determines the particle velocity by measuring the time of flight, ΔT, a particle requires to pass between the front and back detectors, a distance of

ΔX. This added capability provides a third parameter in a two-parameter measurement, thus allowing a separate check on data validity, which is particularly helpful at high incoming particle flux rates.

Full spherical coverage is provided by using a motor subsystem to step the detector assemblies through 225° of rotation every 140 seconds. The subsystem, under separate microprocessor control, can position the telescope assemblies anywhere along the rotation axis with 1.8° resolution. The nominal 30° step every 20 seconds, along with the 3-revolution-per-minute rotation of the spacecraft science boom, provides three-dimensional resolution of particle distribution.

A special wiring assembly, called a polytwist (Fig. 7), carries 116 power, control, and analog signal lines between the rotating platform and the main electronics assembly. The central rotating shaft, through which all the signals must pass, has a maximum diameter of 2.26 centimeters. The polytwist is designed for a 500,000 cycle lifetime.

The detector assemblies use (a) magnetic deflection, (b) absorber materials to differentiate between incoming particle types, and (c) varying aperture sizes to allow operation over a wide dynamic rate range. Radioactive calibration sources are mounted on a ver-
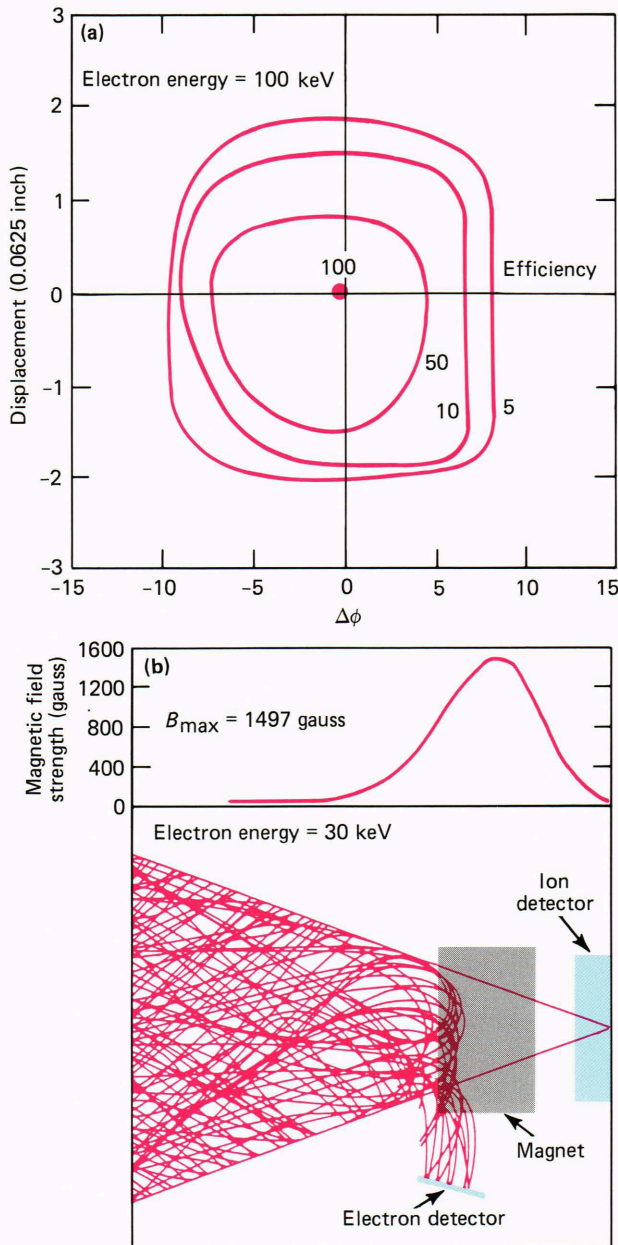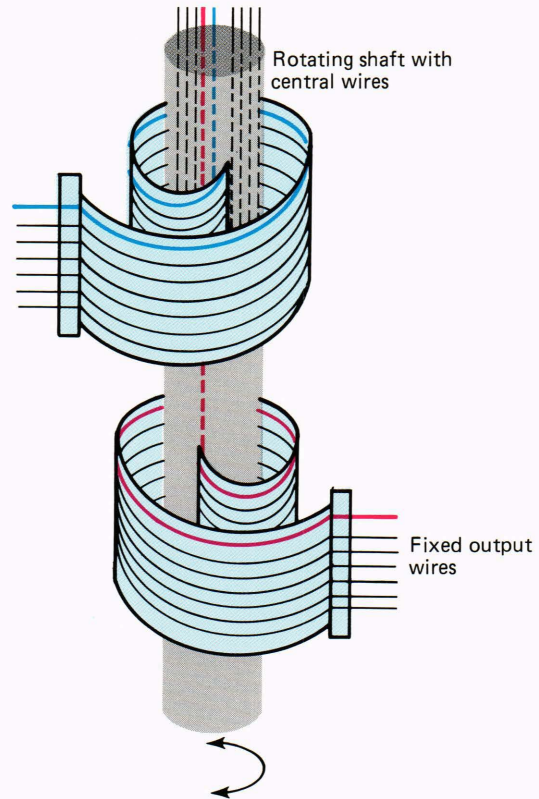
Figure 6—(a) Efficiency contour across the telescope aperture for detecting 100 kiloelectronvolt electrons in a HI-SCALE detector. $\Delta\phi$ is the angle relative to the aperture centerline. (b) Example of a computer simulation for electron trajectory tracing in a magnetic field geometry similar to that used in the LEMS 30 HI-SCALE telescope.

Figure 7—Section of the EPD polytwist assembly showing wire routing.

tical shield that is observed by the telescopes nominally every 140 seconds.

Ion calibration data recorded with the CMS at Rutgers University's Van de Graaff accelerator facility are shown in Fig. 8.

AMPTE MEDIUM ENERGY PARTICLE ANALYZER INSTRUMENT

The Medium Energy Particle Analyzer (MEPA) instrument (Fig. 4c) is measuring the ionic composition of energetic particles in the earth's magnetosphere on the Active Magnetospheric Particle Tracer Explorers (AMPTE) mission's Charge Composition Explorer spacecraft, which was launched on August 16, 1984.[2] The AMPTE mission injects tracer ions (lithium and barium) both inside and outside the magnetosphere. In common with the other satellite instrumentation, the MEPA is designed to measure very low fluxes of the tracer ions in the presence of a large natural background of protons and helium ions, and it will also measure the natural particle populations present over the satellite orbit.
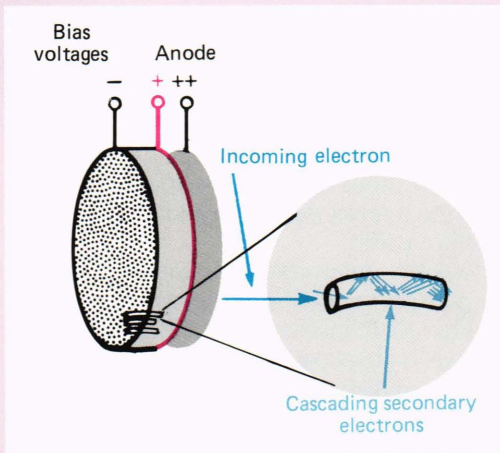
The MEPA determines ion composition by measuring particle velocity and energy ($\Delta T \times E$), as in the Galileo EPD instrument. Unlike the EPD, however, it uses a novel detector system that contains only one silicon solid-state detector and two very thin (1600 and 300 angstrom) foils placed 5 and 10 centimeters in front of the detector. Secondary electrons are emitted from each surface when an incident energetic ion traverses the two foils and stops in the solid-state detector. The electrons are electrostatically accelerated and deflected onto microchannel plates (see the second boxed insert) that provide timing pulses to measure ion time-of-flight between the front and intermediate foils and the rear detector. In addition, particle energy is measured in the rear detector.

The timing information derived from the detectors helps to determine particle mass and reduce the processing of erroneous or undesirable events. An event is considered valid only if the timing pulses oc-

Figure 8—Ion calibration results, ΔE versus E, from an EPD instrument test conducted at the Rutgers University Particle Accelerator Facility. JA' is the front thin detector, and K' is the thick back detector. Straight lines are rate channel boundaries superimposed on particle tracks.
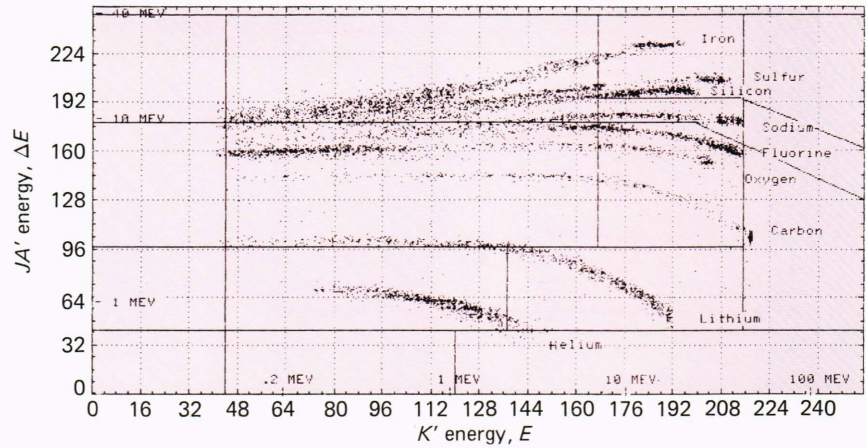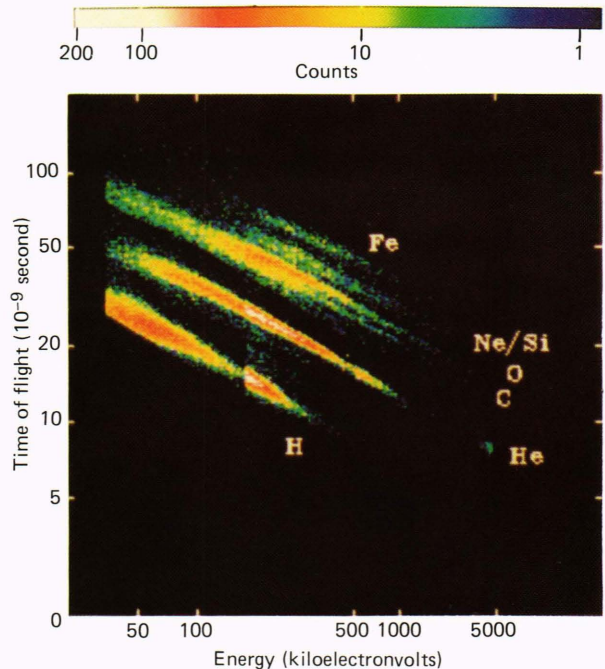
A microchannel plate is an electron multiplier that amplifies signals with one or a few incident ions, electrons, or protons into much larger, more easily measured signals. Physically, it consists of a glass disk, approximately 30 millimeters in diameter by 1 millimeter thick, which is itself a collection of up to several million glass channel electron multiplier tubes. Each incident particle falling on the front of one of these tubes will create secondary electrons that will cascade through the tubes (see the enlargement), producing increasing numbers of secondary electrons. The electrons, eventually numbering up to 2 million, are accelerated by the external bias voltage to the collector anode and result in a sharp current pulse less than 2 nanoseconds wide.

Figure 9—Actual energetic particle data, ΔT versus E, from the MEPA instrument while in orbit on August 28, 1984. ΔT 13 is the measured time of flight between foil 1 and the back detector, and E is the measured energy deposited in the back detector.

cur within a 150 nanosecond interval, if the two measured timing intervals are consistent with each other, and if an energy pulse is detected from the solid-state detector. Only valid solid-state detector signals are passed on to the slower analog amplification and shaping stages. This significant design improvement provides rejection of background events and most protons, which do not generate time-of-flight signals.

The detector system provides ion composition in an energy range of 0.01 megaelectronvolt per nucleon to

over 6 megaelectronvolts for ions from protons to iron. Two-dimensional coverage is provided by the above assembly and another single solid-state silicon detector assembly with a smaller aperture opening. Both assemblies use sweeping magnets to reduce incoming electron fluxes. A radioactive calibration source mounted in front of the detector aperture monitors channel gains throughout the mission life.

Ion composition data from the time-of-flight detector assembly, taken while in orbit soon after launch, are shown in Fig. 9.

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THE AUTHORS

STEPHEN E. JASKULEK (seated) is the systems engineer for the Energetic Particle Detector, which will be flown on the Jupiter-bound Galileo spacecraft. He was born in Cleveland in 1957 and received his B.S. degree in electrical engineering from Washington University in St. Louis in 1979. Prior to joining APL in 1981, he was employed by Rockwell International in their automated test systems group, where he developed high-speed peripheral equipment for use in computer-controlled electronics testing. At APL, Mr. Jaskulek has worked in the Space Department as a systems engineer on the Coast Guard Solar Powered Aids to Navigation project. His interests include advanced computer design for control and data acquisition in space applications.

RICHARD W. MCENTIRE (standing, right) first worked at APL as a summer employee in 1961 while he was an undergraduate. After receiving a Ph.D. in physics from the University of Minnesota, he returned to APL in 1972 as a member of the Space Department's Space Physics Group. He has worked on the development of instrumentation for balloons, rockets, and spacecraft.

Dr. McEntire's current research interests are in the dynamics of plasmas and energetic particles in planetary magnetospheres. He is the program scientist at APL for the Energetic Particle Detector for the NASA Galileo mission and the AMPTE program and is lead investigator for the Medium Energy Particle Analyzer on the Charge Composition Explorer spacecraft.

ROBERT E. GOLD (standing, left) is a senior staff scientist at APL. Born in New York City, he completed his undergraduate studies, in physics, at the City College of New York (B.S., 1965) and continued his work at the University of Denver (Ph.D., physics, 1973), where his research in cosmic rays and the terrestrial magnetosphere included a balloon-launching excursion to Antarctica. During the period between his undergraduate years and graduate school, he was employed in electronics and quartz crystal manufacture.

After a year and a half of post-doctoral research on the sun and interplanetary medium at the University of New Hampshire, Dr. Gold came to the Space Physics Group in 1975. His research at APL has concentrated on the structure of the heliosphere and the propagation of solar energetic particles within it. Since 1978, Dr. Gold has been the project scientist for the HI-SCALE experiment of Project Ulysses (formerly known as the International Solar Polar Mission). Ulysses will be launched in May 1986 and will become the first spacecraft to explore the solar system at high latitudes. Dr. Gold is a member of the American Geophysical Union.