MJU79/COSMIC RAY AND MAGNETOSPHERES INVESTIGATION

TECHNICAL PROPOSAL

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2. ABSTRACT

We propose to measure the spectra and composition of magnetospheric, interplanetary, and interstellar energetic particle fluxes. The angular distributions and absolute intensities of the magnetospheric fluxes in a number of energy intervals will be measured for electrons ($E_e > 0.070$ MeV), protons ($E_p > 0.080$ MeV), helium ions ($E_\alpha > 0.24$ MeV/nucleon), and medium-Z ions ($E_m > 0.3$ MeV/nucleon). The instrument is designed to measure the range of intensities from that of very weak magnetospheres up to and beyond that associated with Jupiter. The measurements will be used to study magnetospheric processes at Uranus and Jupiter, and to determine the orientation, approximate magnitude, and rotational period of the Uranian dipole moment as defined by the presence of energetic charged particles.

The energy spectra and elemental composition of cosmic ray nuclei with $1 \leq Z \leq 26$ will be measured over an energy range from $\sim 0.5 \leq E \leq 500$ MeV/nucleon, and isotopic studies of the fluxes with $1 \leq Z \leq 16$ will be possible from ~ 2 to 75 MeV/nucleon. In addition, cosmic-ray electrons (~ 3-12 MeV) will be studied. Particular emphasis will be placed on the streaming patterns and spectral differences that are expected to occur for different elements at low energies in the outer heliosphere and in interstellar space and which cannot be observed inside of 10 AU. These studies will provide information on possible nearby cosmic ray sources, on both recent and past nucleosynthesis, on the heating and dynamics of the interstellar medium, and on the energetic particle acceleration processes occurring in several different regions. The cosmic rays also serve as probes of the large-scale structure of the heliospheric plasma and fields. In addition, the MJU mission provides the best opportunity for reaching the cosmic ray modulation boundary which is presently estimated to be between 10 and 20 AU.

The characteristics of the three proposed detector systems are outlined in the following summary page. Two of the systems are essentially identical to similar systems on the CRS experiment on MJS '77, while the third system provides comprehensive coverage of the more intense trapped particle fluxes. The third system has beem implemented so that there is no change to the CRS electrical and mechanical interface to the spacecraft and so that only minimal modifications of the CRS electronics are necessary. All three systems consist entirely of solid state charged-particle detectors, which provide the required combination of charge and energy resolution with high stability and reliability.

3. EXPERIMENT SUMMARY CHART

MJU 79/COSMIC-RAY AND MAGNETOSPHERES INVESTIGATION

This experiment consists of three basic detector systems, a Magnetospheric Telescope Array (MTA), a Low Energy Telescope System (LETS) and a High Energy Telescope System (HETS). The MTA includes 4 high count-rate telescopes and 3 omnidirectional detectors. For HETS and LETS multi-parameter analysis is performed essentially over the complete charge and energy range. Solid-state detectors are used throughout.

Charge, Isotope and Energy Range

Nuclei	$(Z = 1)$	0.08 - 10 MeV	(single parameter analysis)
	$(Z = 2)$	0.24 - 5.6MeV	(single parameter analysis)
	$(1 \leq Z \leq 30)$	0.5 - 500 MeV/nuc	(multi-parameter analysis)
Electrons		0.070 - > 28 MeV	
Isotopes	$(Z = 1,2)$	~ 2 - 70 MeV/nuc	$(\Delta M = 1)$
	$(3 \leq Z \leq 8)$	~ 3 - 120 MeV/nuc	$(\Delta M = 1)$
	$(9 \leq Z \leq 16)$	~ 3 - 120 MeV/nuc	$(\Delta M = 2)$

Anisotropies (4 directions)

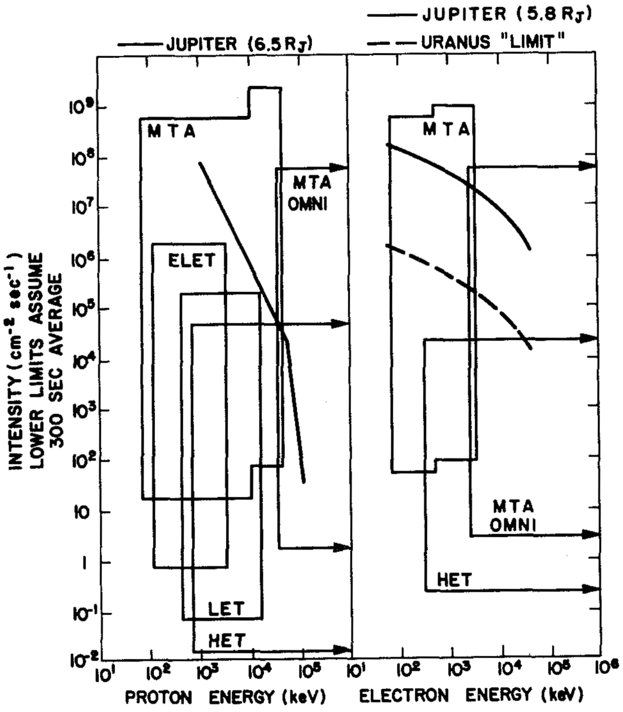
electrons	0.07 - 0.76	MeV
protons	0.08 - 43	MeV
alphas	0.24 - 8.4	MeV/nuc
$6 \leq Z \leq 26$	~0.3 - 18	MeV/nuc

Flux Dynamic Range

Magnetospheres: See Figure. Lower limits assume only 300 sec average.
Cosmic Rays: 10^{-5} to $>10^{4}$ cm^{-2}-sec^{-1}

Geometrical Factors

MTA	0.08 cm^2-sr for telescopes; 0.02 cm^2/omnidirectional detector
LETS	12 cm^2-sr (single parameter) 2 cm^2-sr (multi-parameter)
HETS	1.7-3.4 cm^2-sr (energy dependent)



Weight 7.1 kg (15.6 lb.)

Power 6.8 W

Volume 31.1 cm x 20.3 cm x 17.8 cm high electronics box with detector assemblies extending a maximum of 15 cm additional.

Thermal -25°C to +35°C maximum, -5°C to +15°C preferred.

Calibration Self-calibrating in flight. HETS, LETS and MTA have overlapping energy ranges.

Allowable Material in Field of View

0 mg/cm^2 for MTA telescopes
0 mg/cm^2 for LETS
1 mg/cm^2 for HET (S_1), 50 mg/cm^2 for HET (S_2 + P)

4. SCIENTIFIC OBJECTIVES

I. MAGNETOSPHERIC/PLANETARY PHYSICS

A primary objective of this experiment is the search for magnetospheric phenomena at Uranus as defined by the presence of energetic charged particles. A comprehensive set of measurements of the energy spectra and angular distributions of energetic electrons, protons, helium ions and medium charge ions separately as a function of position will provide a description of the Uranian magnetosphere. These data will be used to:

- delineate sources and sinks of magnetospheric particles, energy flow and distribution, co-rotation, diffusion processes, and satellite sweeping and injection effects.
- determine the orientation and approximate magnitude of the magnetic dipole moment of Uranus and thus the magnetohydrodynamic properties of the planet's interior.
- determine the rotational period of the interior of Uranus and its difference from the rotational period of atmospheric features determined optically.

Another major objective is the search for energetic particles emitted by Uranus and further study of those emitted by Jupiter.

The Jovian flyby will permit further characterization of the magnetosphere of Jupiter at a different epoch in the solar cycle than previous missions and with significantly improved instrumentation.

II. GALACTIC PROCESSES

Another primary objective will be the study of the galactic processes associated with the energetic particle fluxes in the distant heliosphere and beyond. Highly precise measurements of the spectra and elemental and isotopic composition of energetic nuclei as a function of position and direction will contribute in a major way to progress in studies of fundamental astrophysical phenomena, such as

- the direct identification of matter samples from nearby pulsar or supernova cosmic ray sources through measurements of the streaming of interstellar cosmic rays.
- the processes of nucleosynthesis in cosmic ray sources through analysis of identifiable samples of both recent and past element building.
- the properties, dynamics, and heating of the interstellar medium as related to the life history of cosmic rays in the galaxy, particularly at energies below several hundred MeV, which are inaccessible to observers at 1 AU.

III. INTERPLANETARY PHENOMENA

A third objective is the study of the physical processes and features associated with the energetic particles in the heliosphere. Comprehensive measurements of the streaming and the energy, charge, and mass spectra of the particle fluxes will be used in studies of:

- the energetic particle acceleration processes occurring in planetary magnetospheres, interplanetary regions, and in solar flares.
- the large scale structure and properties of the heliospheric plasma and fields as remotely probed by the energetic particles.
- the effective cosmic ray modulation boundary, presently estimated to lie between 10 and 20 AU.

4.1 EXPERIMENT RATIONALE

Prior to MJU, Pioneer's 10 and 11 as well as the MJS mission will have studied the heliosphere out to 10 A.U.. With MJU, exploration of the outer heliosphere will begin. This exploration will include what promises to be a dynamically different magnetosphere - that of Uranus, a completely new regime of interplanetary phenomena and the opportunity to reach beyond the boundaries of the modulation region and make direct observations of low and medium energy galactic cosmic rays.

To take full advantage of this new opportunity, we have given careful consideration to establishing a comprehensive, balanced complement of detector systems capable of defining the magnetosphere of Uranus, gaining new results at Jupiter and possessing the charge, mass and energy resolution to study the interstellar cosmic ray population and new interplanetary phenomena. Our starting point was based on the following considerations (a) The extensive experience of the Iowa group in studying the earth's magnetosphere (b) The very successful efforts of the Iowa and GSFC/New Hampshire groups in exploring the Jovian magnetosphere, and (c) The experience of all groups in cosmic-ray studies with special emphasis on our MJS cosmic ray experiment. We considered the recent advances in our knowledge of planetary magnetospheres and in cosmic-ray phenomena. A major influence was the fact that MJU is a low cost program. With all these factors, it was decided that major emphasis should be placed on studying the Uranian magnetosphere and on extending the charge measurements to lower energies as a diagnostic for both planetary and interplanetary phenomena. For cosmic ray studies, extended charge and energy coverage are vital and these have been retained from the MJS experiment. Cost and weight constraints forced the removal of 1 HET and the TET electron experiment from the MJS complement. For the medium energy cosmic ray nuclear component this is a reduction in redundancy. For cosmic-ray electrons we have decided to place special emphasis on the 3 - 12 MeV energy range as we discuss in the following section.

The resultant system which we propose consists of a magnetospheric telescope array (MTA), a low energy telescope system (LETS), and a high energy telescope system (HETS). Solid state detectors are used throughout. The overall cohesiveness and broad dynamic ranges in energy, intensity and charge for our experiment are illustrated in Figure 4-1 and 4-2. Figure 4-1 shows the large range in energy and intensity over which we can observe magnetospheric electrons and protons. The maximum expected Jovian electron and proton intensities and an estimate of the maximum electron intensity at Uranus (see Appendix A1) are also shown in Figure 4-1. We see that the proposed maximum dynamic range is more than adequate. The minimum measurable intensities in Figure 4-1 assume an integration time of 300 seconds, during which time the spacecraft will traverse ≤ 0.2 R_U, and either 10 observable counts or a counting rate 2 σ above the inherent cosmic ray and RTG produced background.

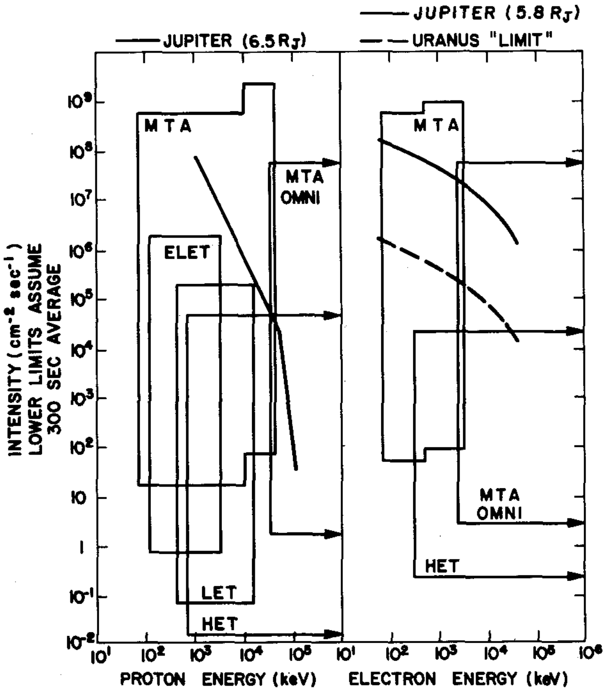


Figure 4-1

The use of multiple telescopes allows the optimization of the charge and energy response and background rejection over a given energy interval and provides the redundancy that is vital for an extended mission. Figure 4-2 shows the overlapping responses of the HETS and LETS (= LET + ELET). The dashed line in the upper part of Figure 4-2 is the lower boundary of the HET penetrating mode, described in Section 7., III. Isotope measurements will be made below this line. The arrow at the top of Figure 4-2 indicates that integral measurements will be made above 500 MeV/nucleon.

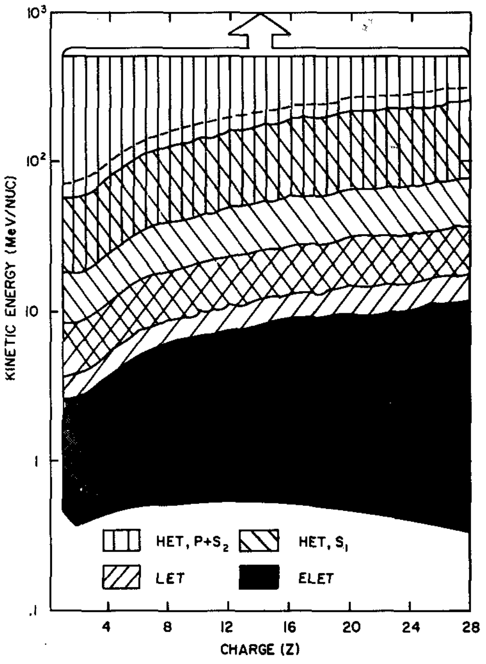


Figure 4-2

The magnetospheric telescope array (MTA) consists of four identical telescopes and three omni-directional intensity monitors contained in spherical shields of different thicknesses. This system will measure the intensities, spectra and anisotropies primarily of electrons, protons, and alpha particles. The four telescopes provide redundancy and large geometrical factors, however the primary purpose of having four is to make anisotropy measurements. We demonstrate in Appendix A6 that adequate anisotropy measurements can be made with this approach. Thus we avoid the risk associated with a mechanical rotation device. We adopt the same philosophy for the LET array (cf. Appendix A5).

The proposed experiment will place particular emphasis on low energy interplanetary phenomena and the low-energy galactic nuclei that can be observed outside or near to the boundary of the heliosphere. Multi-parameter analysis will be extended down to ≤0.5 MeV/nucleon for protons and heavier nuclei up to iron (cf. Figure 4-2). The cornerstone for these studies is the low energy telescope system (LETS) consisting of a set of four identical, mutually orthogonal low-energy telescopes (LETs) and two extended low energy telescopes (ELETs). The method for measuring anisotropies is discussed in Appendix A5. The two ELET telescopes are smaller versions of the LET telescopes, utilizing 6μ thick dE/dx counters (versus 35μ for the LETs). Together the LET and ELET telescopes provide low background, high resolution charge and isotope data with a high sensitivity and statistical accuracy over a broad range of charge and energy as shown in Figure 4-2. The LET and ELET telescopes will also be useful for high-sensitivity studies of weak magnetospheric particles.

The proposed high energy telescope (HET) uses curved dE/dx solid state telescope elements in a special, double ended "thick-thin" arrangement. With this telescope it will be possible to achieve charge resolution up to a $Z \gtrsim 30$, and isotope resolution up to $Z \sim 8$ (for $\Delta M=2$, isotope resolution up to $Z \approx 16$). At the same time the instrument will provide accurate spectra from ~ 4 MeV/nuc up to ~500 MeV/nuc and above for a direct comparison with the comprehensive data available near the earth. The HET telescope has a geometrical factor ~2 times larger than typical earth satellite systems used in the past (~20 times larger than the telescopes now on Pioneer 10 and 11). This large geometrical factor is of vital importance in many areas; for example, we expect to observe ~5,000 Be or Fe nuclei in one year. Differences in chemical composition of spectra of even the less abundant nuclei such as K and Ni will be easily studied in the proposed experiment, whereas this has not been possible on <u>any</u> of the previous IMP, OGO or Pioneer systems. The HET telescope will also measure the electron flux up to ~12 MeV with a high statistical accuracy and temporal resolution. We demonstrate in Appendix A12 our ability to make these measurements in the presence of RTG background.

5. SPECIFIC RESULTS TO BE EXPECTED

I. MAGNETOSPHERIC PHENOMENA

The basic observational results along the respective encounter trajectories at Jupiter and Uranus will be essentially continuous measurements (time resolution 6 sec) of the angular distributions and absolute intensities of energetic charged particles over a broad range of energy and intensity. Analysis of these data will yield important results in magnetospheric physics and planetology, as sketched below.

A. Uranian Magnetosphere

Existing knowledge of Uranus permits a wide spectrum of possibilities on the nature of its magnetosphere as discussed in Appendix A1. These possibilities range from a Venus-like situation to a fully-developed magnetosphere of exotic topology, possibly containing particle intensities intermediate between those at the earth and at Jupiter. Thus, the mission will be able to answer some fundamental questions concerning Uranus. The prime question is whether or not Uranus is a magnetized body. With 1.1 R_U as the radius of closest approach, the magnetic moment of the planet must be less than 4/1000 of that of the earth and/or the intensity of energetic particles near periapsis must be less than 0.002 $(\text{cm}^2 \text{ sec sterad})^{-1}$ in order that no effect be observed with the proposed instrument. Both of these values are far below reasonable expectations.

If a Uranian magnetosphere does indeed exist, our measured angular distributions will determine the direction of the local magnetic vector $(\pm\hat{B})$ on a point-by-point basis for certain simple types of angular distributions, without reference to magnetometer data. This method assumes that the axis of symmetry of the particle distribution is identical to $\pm\hat{B}$ and that the plane of symmetry is perpendicular to $\pm\hat{B}$. If magnetometer data are available, the parameters of more complex angular distributions can be determined. The parametric trial-and-error closure of inbound and outbound omnidirectional intensity curves in the inner magnetosphere of Jupiter has been demonstrated by the Iowa group to be a notably successful method for determining the orientation of the dipole moment of the planet, using particle data only. This method is applicable to Uranus. The rotational period of the interior of Uranus is presently estimated to be only about a factor of 2. It can be determined from the cyclic modulation of particle intensities to an estimated accuracy of ±5%. The magnitude of the magnetic moment can be estimated to within a factor of about 2 using particle data only. All of the above quantities are fundamental to knowledge of the internal magnetohydrodynamics of the planet as well as to the understanding of its magnetosphere.

Analysis of the angular distributions and energy spectra of protons will define the radial extent of corotation and thus define which part of the magnetosphere is dominated by corotation and which is not. Both the proton and electron angular distributions will be used to determine those regions where outward streaming of field aligned particles (which has been conjectured for the case of Jupiter to be the source of energetic particles in the outer magnetosphere) is dominant over convection, another important element in magnetospheric dynamics.

The principal source of energy to drive magnetospheric processes at Uranus will probably be its rotating ionosphere rather than the solar wind, which will be very weak at 19 AU. This is quite a different physical situation from the case of the earth where the solar wind is the dominant source and from the intermediate case of Jupiter. Our angular distributions and broad energy-spectral coverage will provide phase space densities for electrons, protons, helium ions, and medium-Z ions as a function of position. These data in conjunction with data on particle sweeping by the inner satellites of Uranus will give a definitive determination of radial diffusion processes in a rotationally dominated magnetosphere. The radial dependence as well as the energy, charge, and mass dependence of the diffusion process will be determined. The dominant source and loss mechanisms will also be delineated.

The magnetosphere of Uranus is expected to be one of distinctively different physical character than those of the earth and Jupiter because of the unique orientation of its rotational (and probably its magnetic) axis approximately along the planet-sun line and because of the much reduced dynamic pressure of the solar wind at 19 AU (Appendix A1).

B. Jovian Magnetosphere

The observations at Jupiter with a radius of closest approach of 5.8 R_J will be generally repetitive of those made previously by Pioneers 10 and 11 and by two Mariner-Jupiter-Saturn fly-bys but will provide data at a different epoch in the solar activity cycle and at a different specific solar wind situation than those of previous missions. Hence they will be of value on these grounds alone.

Also, the MTA instruments design takes advantage of our experience with traversals of the Jovian magnetosphere by Pioneers 10 and 11. Our large-dynamic-range MTA has advanced capabilities for clean particle identification, accurate energy spectra, and three-dimensional angular distributions under the now-known conditions of the Jovian encounter. Hence, we expect that MJU observations at Jupiter will contribute significantly to a better definition of radial diffusion processes as a function of radial distance, particle energy, mass and charge; of sources and losses; and of particle streaming and corotation.

II. GALACTIC PHENOMENA

Since the MJU mission is designed to reach at least 20 AU (even if one ignores the extended-mission phase), one can hopefully expect to make in situ studies of scientifically significant galactic phenomena. At present the observational evidence bearing on the question of reaching interstellar space indicates that the effective cosmic-ray modulation boundary probably lies between 10 and 20 AU.

A. Measurements of Cosmic-Ray Nuclei

Low-energy galactic particles are probably prevented from reaching the earth because of interplanetary energy loss. Therefore, measurements on MJU may provide the first determination of the total interstellar cosmic-ray energy density which is a basic quantity of importance in galactic dynamics and in the understanding of the evolution and stability of the galactic disk structure.

The proposed detailed measurements of the spectrum and abundance of the individual cosmic-ray nuclei allow the study of two particularly important problems relating to the origin of cosmic rays. One is a determination of the injection spectrum and source abundance of the nuclei, the other is an understanding of the propagation of the cosmic ray nuclei in the galaxy. We shall now give some examples of specific measurements and what they can tell us about these astrophysical problems.

1. Measurements of the spectra and abundances of generically-related primary and "secondary" groups of nuclei: One such group of nuclei is the so-called "quartet," ^1H, ^2H, ^3He, ^4He. The secondary nuclei ^2H and ^3He are produced almost entirely from ^4He, and their production cross sections are well known. Similarly, Li, Be and B are primarily products of primary C and O, and nuclei in the charge range $Z \doteq 17$-25 are fragmentation products of primary

Fe nuclei. The interstellar spectra of these nuclei, which contain important information on the interstellar propagation, cannot be measured at energies ∿100 MeV/nucleon at 1 AU.

Consider the low energy He spectrum as shown in Figure 5-1. The origin of the flat portion of the He spectrum between 5 and 100 MeV is essentially unknown. This flat spectrum could be related to the anomalous N and O spectra discussed later, or it could have an entirely different origin. In either case, it is crucial for the interpretation of this behavior to simultaneously measure the ^{2}H and ^{3}He components down to the very lowest energies.

A particularly interesting set of nuclei to study are the electron capture isotopes such as ^{7}Be. A study of these isotopes at low energies, where the electron capture cross section changes rapidly with energy, may give definitive information on the material densities in regions where the cosmic rays are accelerated or propagate.

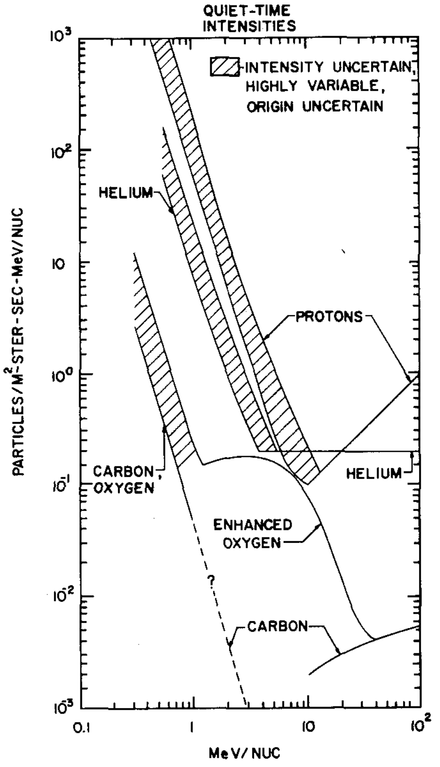


FIGURE 5-1

2. Measurements of the low-energy part of the spectra of all nuclei: At low energies the effects of ionization energy loss on different charges in interstellar space should be an important signature of cosmic-ray propagation and source distribution. For example, the range of a 1 MeV proton in typical galactic magnetic fields is ∿200 pc with a lifetime of ∿10^4 years. Because of the Z^2/β^2 effect this ionization energy loss will result in charge dependent compositional changes at low energies, which are indicative of localized propagation effects, and possibly the existence of separate and localized cosmic ray sources. A comparison of chemical abundances at low and high energies will therefore be crucial to the separation of features related to the cosmic-ray injection and to the subsequent particle propagation in the galaxy. An example of this is the recently discovered anomalous (enhanced) abundances of N, O and Ne below ∿40 MeV/nucleon (see Figure 5-1 and Appendix A3).

The specific details of the low-energy spectra, particularly for the heavier nuclei, are important from the point of view of the role of cosmic rays in the dynamics of the galaxy. Because of the Z^2 effect, determination of the role of cosmic rays in the heating of the interstellar medium by ionization loss, and in galactic X- or γ-ray production, requires the study of the spectra of all the nuclei at the lowest energies.

3. Study of the particle flow patterns (anisotropies) of protons, helium, and heavier nuclei: We believe that a study of the anisotropies of

galactic cosmic rays below ∿100 MeV/nucleon and down to the lowest possible energies will be especially fruitful. Although the anisotropy observed near earth at very high energies ($\gtrsim$100 BeV) is certainly small, any attempt to estimate the anisotropy of the bulk of the cosmic rays (1 BeV and below) at present is sheer speculation. The magnitude of the anisotropy might vary widely with energy depending upon the distribution of cosmic-ray sources in the galaxy (see Appendix A4).

A basic point is that anisotropy and composition studies provide complementary information on the local cosmic-ray source distribution and local propagation parameters in the galaxy. A study of the anisotropy of low-energy cosmic rays may also be essential to determine the origin of the particles that are observed.

B. Electrons

The existence of several separate populations of electrons at low energies is clearly evident (see Appendix A2) in contrast to the situation at higher energies (>100 MeV) where these particles are clearly galactic. As a result of this complex situation, the galactic component is unknown at lower energies. Extrapolation to interstellar space is not possible because radio emission from synchrotron radiating electrons below ∿100 MeV is not observable. The direct measurement of the galactic intensity of these electrons will thus be important from several points of view. Since the expected secondary spectrum of knock-on electrons is quite well defined, a measurement of the actual low energy electron flux may be used as a direct test of current propagation ideas. Conversely, differences of the predicted and measured electron spectrum may be indicative of other sources of electrons, of the characteristics of the origin of a low energy primary component, or of spatial non-uniformities in the interstellar electron or proton population.

III. INTERPLANETARY PHENOMENA

It is clear that energetic particle acceleration processes are widespread and are now observed in almost all kinds of plasma conditions in the solar environment and throughout the universe. One of the most impressive results from Pioneers 10 and 11 and other interplanetary spacecraft concerns the complex populations of energetic particles that co-exist in the interplanetary medium. Co-rotating solar streams (mainly protons) are very prominent and may be augmented by interplanetary acceleration effects. These particles co-exist with streams of electrons from Jupiter which are spread throughout the solar system. Closer to the planets (e.g., Earth and Mercury) locally-accelerated protons and electrons are observed. Outside of the directly accelerated solar population, we have no information on the charge composition of the various populations nor do we understand yet how the particles are distributed throughout the solar system.

A. Solar Energetic Particles

Generally, prior to Pioneers 10 and 11, it was felt that the fluxes of solar energetic particles would decrease to insignificant levels beyond ∿5 AU because of energy loss effects and simple spatial expansion. Observations on Pioneers 10 and 11 show significant solar particle fluxes even at 5 AU, however, sometimes exceeding those observed at earth - particularly at low energies. A study of the properties of these events beyond ∿10 AU will give important information on the dynamic properties of the outer heliosphere - particularly interplanetary acceleration and deceleration effects at low energies. The diffusive and convective properties (e.g., radial dependences) of the interplanetary medium will be mapped using the solar energetic particles as probes. The injection of low energy solar particles into the interstellar medium may typify an important stellar phenomenon and will be measured for the first time on the MJU spacecraft.

B. Planetary Energetic Particles

The large transient increases of MeV electrons from Jupiter are the most prominent feature of planetary energetic particles observed in interplanetary space. The manner in which these particles escape from Jupiter's magnetosphere and propagate throughout the solar system is unknown at present. Detailed studies of the energy spectrum, time variations and anisotropies of these electrons up to ∿10 MeV are needed to answer this question.

It is quite possible that the bulk of the low energy electrons observed at earth and throughout the inner solar system arise from Jupiter. To prove this, one will need measurements beyond 10 AU which will be of particular importance in separating these electrons from the true interstellar population. It is also quite likely that electrons will be observed from Saturn and Uranus and a mapping of their intensity near these planets will provide valuable information on the large-scale field characteristics near these planets.

Much weaker fluxes of MeV protons have also been observed from Jupiter in interplanetary space. Again, it is likely that such particles will be emitted by Saturn and Uranus. A study with ELET and LET of the elemental and isotopic abundances of this nuclear population should provide valuable information on the origin of these particles in planetary magnetospheres.

C. Interplanetary Accelerated Energetic Particles

Recent observations of the intensity of low energy solar streams at different radial distances have revealed that interplanetary acceleration of cosmic rays may be a far more important phenomena than was originally believed. This phenomenon could be strongly radially dependent and might be significantly more important in the outer solar system. These effects have been mainly observed for protons in the MeV range and below. They seem to be confined to localized regions of space possibly related to the magnetic field and plasma parameters in these regions. The ELET telescopes will permit extended studies of these particles to be made including the presence of any heavier nuclei. See Appendix A2 for further discussion.

D. Low Energy Quiet Time Turn Ups

The spectra of protons, helium nuclei, carbon and oxygen and possibly other heavier nuclei as well are observed to turn up at very low energies during quiet times when no obvious solar particles are present. These turn ups are very complex and appear to be charge dependent (see Fig. 5-1). The turn ups are very abrupt and the spectra below the turn ups are very steep, $\sim E^{-3}$, suggesting a totally different origin for these particles. It is possible that these particles represent a quiet-time component of the interplanetary acceleration process just discussed (e.g., a Fermi acceleration process operating in interplanetary space). Measurements of the elemental composition down to 0.5 MeV/nucleon is essential to an understanding of the origin of these particles.

E. Anisotropies and Flow Patterns of Galactic and Solar Energetic Particles

The ability of our LET detector system to comprehensively measure anisotropies provides an opportunity to study energetic particle transport in the solar wind. A measurement of the anisotropies provides an indication of the relative importance of perpendicular and parallel diffusion and convection and can help define particle gradients out of the ecliptic plane. Anisotropy measurements complement intensity and composition measurements in the identification of the various energetic particle populations and their mode of transport and possible acceleration in the interplanetary medium. A study of the flow patterns also provides information on the large scale magnetic field properties which are unobtainable by in situ magnetic field measurements.

F. Solar Modulation of Galactic Particles and the Radial Gradient

The solar wind modulates the intensity of galactic cosmic rays over a wide range of energies, with the effect being most severe at the lowest energies. Associated with this modulation must be a radial gradient of the cosmic-ray intensity. Evidence from Pioneer 10 and 11 indicates that this gradient is relatively small out to $\sim$5 AU ($\sim$5% per AU for particles of several hundred MeV/nucleon ; $\lesssim$10% AU for lower energy protons and helium nuclei). How far do these small gradients extend? Is this indicative of a smaller total solar modulation than expected or will the gradients become larger as one approaches the boundary? One of the primary goals of this experiment will be to search for this boundary out to 20 AU and beyond. Basic aspects of energetic particle transport theory in interplanetary space depend upon parameters at this boundary, and they are completely unknown.

Our detector system is designed to very precisely measure the radial gradient and overall modulation as a function of rigidity over a wide range of energy and charge-to-mass ratio in regions not yet penetrated by spacecraft. Various isotopes (such as ^1H, ^2H, ^3He, ^4He) can be used to distinguish between solar, planetary and galactic particles. Electron measurements will also be of great importance. In particular, measurements of the electron gradient and modulation over the energy range from 3-10 MeV and beyond $\sim$10 AU will define the transport parameters over a rigidity range not readily accessible using low-energy proton measurements.

6. EXPERIMENT DESIGN PHILOSOPHY AND APPROACH

The quantities which we propose to measure in order to meet our scientific objectives have been summarized earlier in Section 4.1. These measurements will be made with three detector systems: the Magnetospheric Telescope Array (MTA), the Low Energy Telescope System (LETS), and the High Energy Telescope System (HETS). These three systems share a rich heritage of scientific and technical experience through the combined experience of our four laboratories. The MTA design is an improvement upon detector systems flown to Jupiter by Iowa and GSFC/UNH on Pioneers 10 and 11. The LET and HET systems have evolved from the GSFC/UNH Pioneer 10 and 11 experiments and the Caltech IMP 7 and 8 experiments. With but one exception, the LET and HET systems are identical to those already developed for MJS. The exception is that the LET system has been augmented by two extended low energy telescopes (ELETs); these replace the second HET in the MJS design. The ELETs have their precursor in the GSFC VLET presently being developed for ISEE-C.

By using three independent systems we have been able to optimize the experiment's charge and energy resolution, background rejection and response to high counting rates. We have minimized Landau effects by choosing the thickest dE/dx device appropriate to a given energy interval; we have incorporated three parameter analysis wherever practical; we have incorporated or have deliberately omitted anti-coincidence detectors; we have carefully designed arrays of telescopes for the measurement of anisotropies. Our telescopes consist entirely of solid-state charged-particle detectors. These devices have proven to be uniquely reliable in space applications, in addition to being free of gain changes and having superior, low-noise performance. Finally three independent systems and multiple telescopes provide the redundancy so necessary for extended missions. In summary, we feel that these systems are in an advanced state of development and can be flown as we propose them.

7. INSTRUMENTATION

The overall package we propose is assembled using the same approach used for MJS. This is illustrated schematically in Figure 7-1. The operation of each subsystem is summarized below. More extensive descriptions may be found in the Appendices.

I. MAGNETOSPHERIC TELESCOPE ARRAY (MTA)

A. General Description

The MTA consists of four identical three-element telescopes denoted by R, S, T and U, with physical collimation for directionality, and three spherically-shielded, single element detectors, denoted by M, N and P. These are illustrated in Figure 7-2. All of the detecting elements used in the telescopes are totally depleted silicon surface barrier detectors. The spherically shielded detectors are one-millimeter cubes of lithium-drifted silicon. The axes of the four telescopes are in a symmetric tetrahedral arrangement with an angle of 109° between each pair for the purpose of angular distribution measurements. The physical design and the use of delay-line pulse clipping and fast electronics (50 to 150 nanoseconds) makes it possible to distinguish electrons, protons, helium ions, and medium-Z ions and to separately measure their absolute energy spectra and angular distributions under high intensity conditions such as those that exist in the Jovian (and possibly the Uranian) magnetosphere. A basic time resolution of 6 seconds is proposed, with 96 seconds for a complete cycle of data channels and analyzer elements. The MTA is also valuable for interplanetary measurements at much lower time resolution.

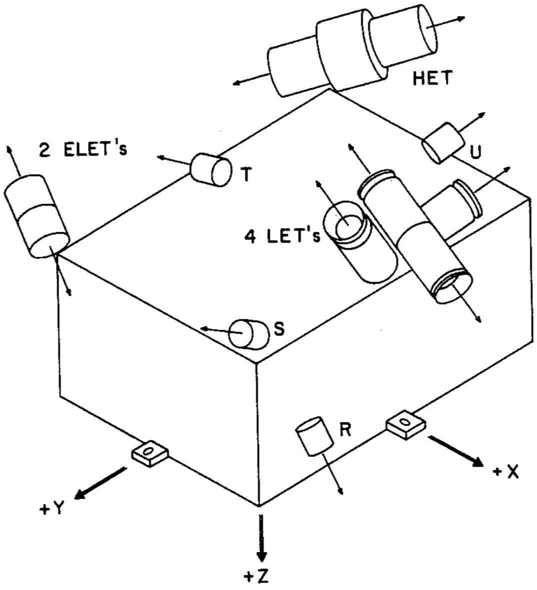


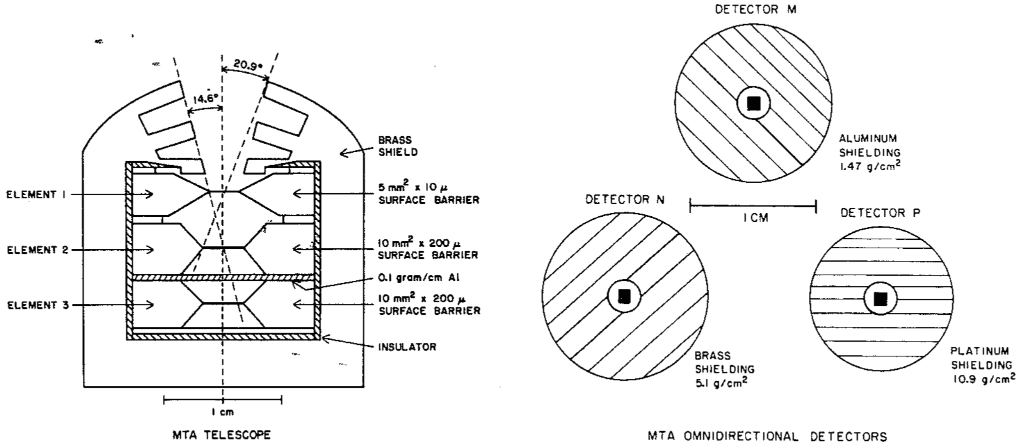
FIGURE 7-1

B. Particle Energy Measurements

Angular distributions and absolute intensities of energetic charged particles in a number of energy ranges are measured as follows:

(1) Electrons ($E_e > 0.070$ MeV)
(2) Protons ($E_p > 0.080$ MeV)
(3) Helium Ions ($E_\alpha > 0.24$ MeV/nucleon)
(4) Medium-Z Ions ($E_M > 0.3$ MeV/nucleon),

all separately.



MTA TELESCOPE

MTA OMNIDIRECTIONAL DETECTORS

FIGURE 7-2

This is made possible by properly selected electronic discrimination levels on the various detectors and by transmitting single element counting rates and combinations of coincidence and anti-coincidence counting rates. An overall summary of the spectral coverage is given in Figure 7-3. Analytical details are given in Appendix A6. The unidirectional geometric factor for the telescopic measurements is 0.02 cm^2 sr and the omnidirectional geometric factor for the cubical detectors is 0.02 cm^2.

C. Dynamic Range in Intensity

Based on Pioneer 10/11 observations, the greatest unidirectional intensities that will be experienced by MJU during its Jovian fly-by are:

$j(E_e > .040 \text{ MeV}) = 5\text{x}10^7/\text{cm}^2\text{-sec-ster};$
$j(E_e > 0.55 \text{ MeV}) = 2\text{x}10^7/\text{cm}^2\text{-sec-ster};$
$j(E_e > 5.0 \text{ MeV}) = 2.4\text{x}10^6/\text{cm}^2\text{-sec-ster};$
$j(E_e > 21 \text{ MeV}) = 1.6\text{x}10^4/\text{cm}^2\text{-sec-ster};$
$j(0.61 < E_p < 3.41 \text{ MeV}) = 7\text{x}10^6/\text{cm}^2\text{-sec-ster};$
$j(1.2 < E_p < 2.51 \text{ MeV}) = 2.4\text{x}10^6/\text{cm}^2\text{-sec-ster};$
$j(14.8 < E_p < 21.2 \text{ MeV}) = 1.6\text{x}10^5/\text{cm}^2\text{-sec-ster}.$

At all single-element counting rates up to about $3\text{x}10^5$ counts/second the MTA output will be linear and simple in interpretation. At the highest expected rates ($\sim 1\text{x}10^6$ counts/second) near periapsis of the Jovian encounter, non-linear effects will be significant but the output will be interpretable in a straightforward way by use of laboratory calibration data. Intensities at Uranus are almost certainly much less than those quoted above.

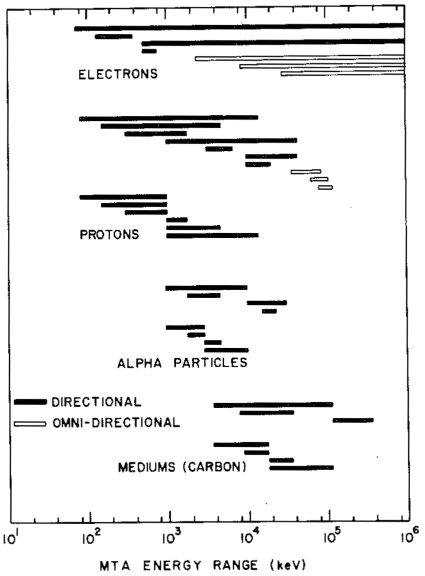


FIGURE 7-3

II. THE LOW ENERGY TELESCOPE SYSTEM (LETS)

A. General Description

The Low Energy Telescope System (LETS) is designed to determine the three dimensional flow patterns of interstellar and interplanetary cosmic ray fluxes and to extend high resolution elemental measurements ($1 \leq Z \leq 30$) down to very low energies. The LET system consists of 6 telescopes, four Low Energy Telescopes (LETs) and two Extended Low Energy Telescopes (ELETs). The four LETs have been optimized for the interstellar anisotropy measurements by incorporating large area, thin detectors. This arrangement, shown in Figure 7-4, provides multiparameter analysis capability at low energies with the relatively large geometrical factor (0.5 cm^{2}sr each) needed for measuring the expected anisotropies (see Appendix A4). The four LETs are required in order to completely characterize the three-dimensional anisotropy (see Appendix A5 for a derivation of this requirement). This geometrical arrangement has been accommodated for the CRS instrument on MJS77 and we would retain precisely the same orientation on MJU79. The four LETs provide not only the anisotropy information, but also an increased geometrical factor ($\sim$2 cm^{2}sr total), and sensor redundancy.

The two ELETs (see Figure 7-4 and Appendix A7) have been optimized for multiparameter analysis at very low energies through the use of ultra-thin detectors. The multiparameter analysis provides high resolution measurements of the spectra and elemental composition of solar and galactic cosmic rays with energies a factor of 3 to 10 lower than possible with LET. For spectra softer than $J(>E) \sim E^{-2}$, the increased flux at the lower threshold more than compensates for the small geometrical factor.

B. Modes of Operation

Two basic modes of operation will be implemented for each of the 6 telescopes, corresponding to double and triple parameter analysis. In addition, a limited single-parameter analysis will be performed on two of the LETs.

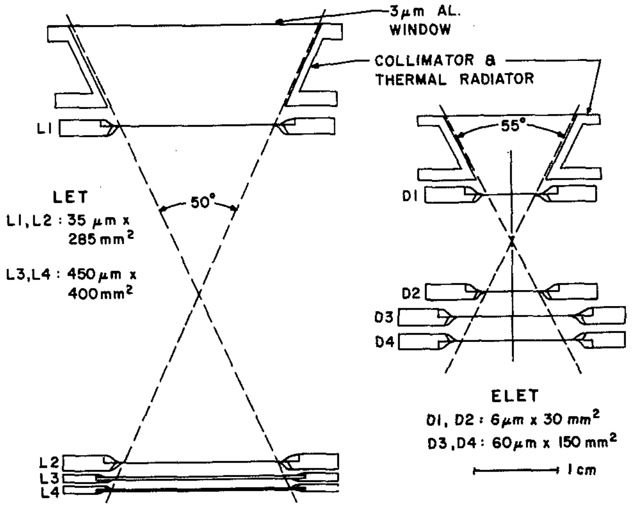


FIGURE 7-4

In the double-parameter mode, characterized by L1L2$\overline{L3}$ for LET or D1D2$\overline{D3}$ for ELET, the particle energy loss is determined in L1 or D1 and the residual energy is measured in L2 or D2. The dE/dx-E analysis provides unambiguous element identification, with isotope resolution in the LETs for adjacent isotopes with $Z \lesssim 5$ and for even isotopes with $Z \lesssim 12$ (see Appendix A8).

In the triple parameter mode (L1L2L3$\overline{L4}$ for LET or D1D2D3$\overline{D4}$ for ELET), the particle's energy loss is measured twice, and the residual energy is measured in L3 or D3. The double-dE/dx measurement both improves the mass resolution and significantly reduces the background due to interacting particles and edge effects. The analysis interval for the D1D2D3$\overline{D4}$ mode corresponds to particle ranges $12 \leq R \leq 72\mu m$ of Si. This interval has been chosen to completely overlap the L1L2$\overline{L3}$ interval, which corresponds to $35 \leq R \leq 70\mu m$ of Si. Similarly, the L1L2L3$\overline{L4}$ analysis interval ($70 \leq R \leq 520\mu m$) has been chosen to provide significant overlap with the HET three-parameter mode. Table 7-1 provides further details. Note that at these energies the heavier nuclei are likely enhanced compared to the relative abundances assumed in the table.

Table 7-1: Typical LETS Interplanetary and Interstellar Analysis Rates

	Energy Interval 1) (MeV/nuc)		Interplanetary 2) Events/6 hr		Interstellar 3) Events/yr		Min. Interstellar Anisotropy 4)	
Nucleon	ELET	LET	ELET	LET	ELET	LET	1 mo.	1 yr.
H	0.46-2.5	1.7-8.4	1.2×10^{4}	1.4×10^{5}	1.7×10^{5}	5.5×10^{5}	3%	1%
He	0.37-2.5	1.6-8.4	10^{3}	800	1.0×10^{4}	3.1×10^{4}	12%	3%
O	0.52-5.2	3.3-18	10	4	600	2.0×10^{3}	24%	13%
Mg	0.55-5.8	3.6-26	~ 1	0.4	140	600	-	24%
Fe	0.38-6.9	3.8-35	~ 1	0.2	100	450	-	28%

1) Energy interval for multiparameter analysis.
2) Assumes $J(>E) = E^{-2}$ as a minimum intensity corotation flux.
3) Assumes $dJ/dE \sim W^{-2.65}$ as conservative interstellar spectra.
4) Assumes a 3σ difference in the counting rates of 2 LETs.

In the single-parameter mode (L1$\overline{\text{L2}}$), only detector L1 is penetrated by the particle. The acceptance cone is defined by the combination collimator and thermal radiator, resulting in a geometrical factor of $\sim$5 cm^{2}sr. The analysis is performed by 4 discriminators chosen for optimum response to H, He, CNO and Z > 8, respectively (see Appendix A8). This mode will be useful for interstellar or interplanetary spectra softer than E^{-2}. The multiparameter ELET analysis will provide unambiguous elemental composition in the same energy interval which will aid interpretation. The primary advantage of the single parameter mode is the large $A\Omega$ which permits determination of the anisotropies of $\sim$1% in one month (based on a 3σ difference in the counting rates). Intercalibration of the telescopes in the laboratory and during interplanetary cruise will be directed toward limiting the systematic uncertainties to $\lesssim$1%.

C. Trapped Radiation Response

The large $A\Omega$ of the LETs is well suited to the detection of very weak magnetospheres. Assuming that a minimum detectable signature corresponds to an increase of 10 counts in a distance of $\sim$0.2 R_U (which the spacecraft traverses in $\sim$300 seconds), then a minimum magnetospheric counting rate of 0.03 sec^{-1} is required. The corresponding minimum fluxes are indicated in Table 7-2, as are the maximum analyzable fluxes which result in a counting rate of 10^5 sec^{-1}. The flux dynamic range of LETS complements the higher flux range of the MTA. In addition, the LETS will provide elemental composition measurements over the range of fluxes in Table 7-2.

Table 7-2: LETS Trapped Proton Response

	Minimum Energy (MeV)	Detectable Flux (cm^{-2}sec^{-1}sr^{-1})	
		Min.	Max.
D1	0.12	~6×10^{-2}	~2×10^{5}
D1D2	0.55	~6×10^{-1}	~2×10^{5}
L1	0.45	~6×10^{-3}	~2×10^{4}
L1L2	1.7	~6×10^{-2}	~2×10^{4}

III. THE HIGH ENERGY TELESCOPE SYSTEM (HETS)

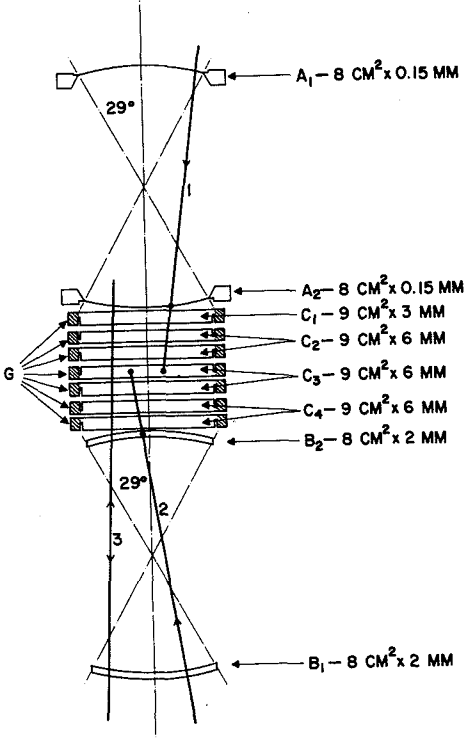
A. General Description

The MJU High Energy Telescope shown schematically in Figure 7-5 has already been developed for use on MJS. It is entirely solid state and makes use of detector technology previously proven on Pioneers 10 and 11, IMPs 7 and 8, and more recently on Helios. The HET system has the following characteristics:

(1) The spectra of electrons and all elements from hydrogen to iron will be measured over a broad range of energies, e.g., 4-500 MeV/nucleon for Z = 1, 2. (2) Individual isotopes will be resolvable up through the isotopes of oxygen ($\Delta M = 1$ for Z = 1-8); individual charges will be resolvable up through Z = 30. (3) The use of a double-ended telescope and the inclusion of a solid-state guard element permits up to a twenty-fold increase in geometry factor over earlier designs.

B. Modes of Operation

A HET telescope has three basic modes of operation, two corresponding to particles that stop within the telescope (denoted by S_1 and S_2), and one corresponding to particles that penetrate the telescope (denoted by P). In the S_1 and S_2 modes, the telescope operates in a standard dE/dx x E mode. The design of the instrument is, however, new and unique to MJU/MJS in that the detector stack serves double duty: S_1 and S_2 correspond to particles entering opposite ends of the telescope. Trajectories 1, 2 and 3 in Figure 7-5 are typical S_1, S_2 and P events, respectively. Table 7-3 summarizes the characteristics of these three modes.



HIGH ENERGY TELESCOPE (HET)

FIGURE 7-5

TABLE 7-3: HET MODE CHARACTERISTICS

Mode	Type of Analysis	Proton Energy Range (MeV)	Coincidence Condition	Detectors Analyzed	Geometry Factor (cm^2-ster)	View Angle
S_1	dE/dx vs. E	4- 57	$A_1A_2C_4G$	$A_1,A_2,C_1+C_2+C_3$	1.0-1.7	58°
S_2	dE/dx vs. E	18- 70	$B_1B_2C_1G$	$B_1,B_2,C_2+C_3+C_4$	0.9-1.7	58°
P	Triple dE/dx	70-500	$B_1B_2C_1$	$B_1,C_1,C_2+C_3+C_4$	1.7	46°

In both the S_1 and S_2 modes isotopic resolution with $\Delta M = 1$ will be possible up to Z = 8 and resolution with $\Delta M = 2$ up to Z = 16. Resolution of adjacent charges is possible up to Z = 30. The isotopic resolution of a telescope built by the Caltech members of our team is illustrated by the accelerator calibration data shown in Figure 7-6. A detailed discussion of background and resolution is presented in Appendix 10.

In the S_2 mode precise measurements of the electron spectrum in the 3-10 MeV interval will also be made. Below 3 MeV, background due to Compton electrons from the spacecraft radio-isotope power supplies will prohibit quiet-time electron measurements. However, interplanetary electron increases due to solar flares and in the vicinity of Jupiter will be observable below 3 MeV. See Appendix A12.

Appendix A9 presents a more detailed description of the HETS design. Table 7-4 summarizes the HETS response to galactic cosmic rays.

IV. ELECTRONIC AND MECHANICAL SYSTEMS

A. Introduction

We have designed this MJU experiment in such a way that the interfaces to the Mariner spacecraft, both electrical and mechanical, are identical to that of our CRS experiment on the MJS spacecraft. Since the HET and LET telescopes are identical to those on MJS, identical electronics will be used. Additionally, for the MJU design, the ELET analog inputs simply replace those of one of the two HET telescopes in the electronics designed for MJS.

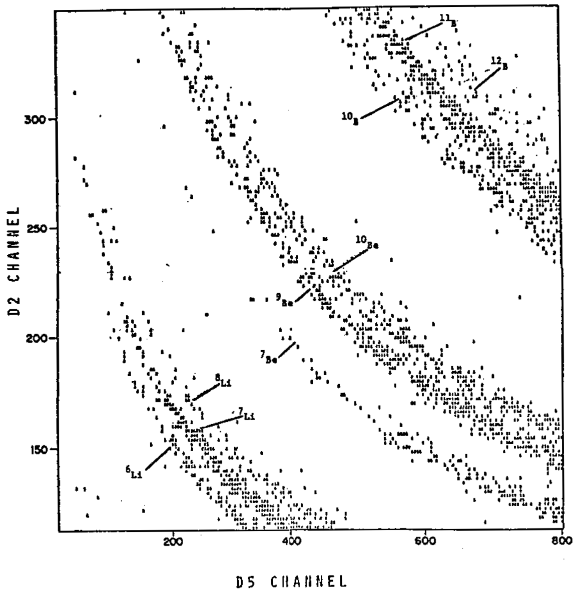


FIGURE 7-6

Table 7-4: HETS Galactic Cosmic-Ray Response

Nucleus	S MODE*			P MODE		
	Energy (MeV/nuc)	Events/Month		Energy (MeV/nuc)	Events/Month	
		1 AU	Interstellar+		1 AU	Interstellar+
H	4-70	1.5×10^4	4.8×10^5	> 70	2.1×10^6	3.6×10^6
He	4-70	5.5×10^3	2.5×10^4	> 70	1.7×10^5	2.0×10^5
Be	5.2-91	2.0×10^1	8.9×10^1	> 91	5.0×10^2	5.5×10^2
O	8.7-154	2.6×10^2	1.3×10^3	>154	4.6×10^3	5.0×10^3
Fe	13.5-295	5.7×10^1	2.2×10^2	>295	4.1×10^2	4.5×10^2

*$S = S_1 + S_2$

+Interstellar intensities are derived assuming a total-energy power-law spectrum.

The MTA is optimized for planetary encounter and based on our own recent experience in the Jovian magnetosphere with Pioneers 10 and 11. It is a direct outgrowth of the GSFC/UNH LET-II telescopes on Pioneer 10/11 and the Iowa G2 detector on Pioneer 11. These sensors and experiments functioned well, and this proposed MJU system provides substantially superior performance in terms of: high count-rate capability; the ability to clearly separate electrons, protons and alphas at high count-rates; and simultaneous measurements in several directions. This latter point - simultaneous measurements in several directions - is essential in light of the Pioneer 10/11 experience where marked changes in angular distributions occurred within a time less than the complete spacecraft rotation of 12 sec. A system employing shared counting registers to mechanically rotated detectors would have more limited temporal resolution.

B. Electronics

The page restrictions for this proposal allow only a short discussion of the most important considerations here. Appendices A6, A7, A8, A9 and A 11 contain more complete discussions.

The charge-sensitive preamplifiers and shaping amplifiers used in this experiment have severe requirements placed on them which we have already attained. Our circuitry for the L_1 and L2 detectors of LET has a system noise performance of ∿55 KeV Si fwhm at room temperature. L_1 and L_2 have a detector capacitance of ∿900 pf, and our design will allow a clean logic threshold to be set at 200 KeV with substantial margin. Many of the preamplifiers/amplifiers in HETS are required to have a linear dynamic range in excess of 32,000. This is accomplished in a gain-switching preamplifier which was invented for the purpose (patent in process), together with a system of 4096 channel pulse-height analyzers. The linear systems for HETS and LETS use shaping time constants of ∿1μsec. The MTA and omnidirectional detectors, however, place different requirements on the electronics. A large dynamic range in energy is not needed. Speed and freedom from pulse pileup effects are required and dictate the fast time constants used - 150 nanoseconds with a 50 ns logic strobe. These systems will allow measurement of energetic particle fluxes substantially greater than those encountered at Jupiter.

The performance of the 4096 channel pulse-height analyzers is competitive with good laboratory spectroscopy systems, having integral and differential linearity of 0.1% and 2%, respectively. Total system gain stability (∿0.1%) is verifiable directly from the flight data from the end points in the response matrices for the various nuclei. Stability of the MTA can be checked because of the way in which the four identical telescopes share parallel electronics (see Appendix A6). An electronic calibrator allows fast, accurate tests of many linear channels for ground and in-flight testing. The experiment includes an extensive data aystem using both RCA COSMOS (JPL radiation-hardened version) and custom-designed LSI circuitry. In addition to 36 registers for storing the many different kinds of events for the three-telescope systems, it includes 64 24-bit counters for rate data.

C. Reliability/Redundancy/Flexibility

Any experiment being designed for an MJS or MJU mission must devote considerable effort to the subject of reliability - both in terms of an aging lifetime and a radiation-damage lifetime. All parts are procured and tested to the JPL-approved MJS program. Experiment lifetime should not be limited by electronics parts lifetime. Extensive testing and analysis by the experiment team and JPL for the MJS experiment lead to the conclusion that from a radiation point of view, the limiting components are the JPL-supplied COSMOS circuitry which are in every experiment and system. Their tolerance appears to allow a comfortable margin at Jupiter.

Six-year missions clearly require careful consideration of redundancy and possible failure modes within the experiment. The fact that we've chosen multiple detectors with parallel electronics permits this experiment to tolerate several serious failures and still make significant measurements. An extensive command system allows major reconfiguration within the experiment and also allows power on/off at the circuit level - for instance individual preamplifiers. The experiment and the spacecraft allow considerable flexibility in the on-board data format. At expected bit rates, the important comparative MTA data is updated nominally every six seconds.This period can be shortened or lengthened in a binary fashion by command, and also the fraction of experiment telemetry devoted to the various detector systems can be similarly changed. Appendix A 11 furnishes a more complete discussion.

D. Data Rate and Storage

A nominal experiment data rate of $\sim$128 bps is envisioned for cruise, although the experiment can be commanded for operation at lower and higher bit rates. At planetary encounter we require $\sim$256 bps. In the case of extended periods without real-time tracking from earth, we require the assignment of $\sim$1/5 of the spacecraft buffer memory for storage of this experiment's data. This would allow $\sim$15 bps for one week's storage, for instance, and would allow: storage of all high Z pha events; a significant sampling of the proton and alpha particle spectra ($\sim$10 events per minute); and storage of the complete rate data with basic accumulation times of $\sim$15 minutes.

E. Weight, Power and Volume

The heavy dependence of this experiment upon the instrumentation designed and built for MJS allows us to predict the performance, weight, power, volume and cost requirements accurately. The details are given in Appendix A 11.

Weight: 7.1 Kg
Power : 6.8 Watts
Volume: 31.1 x 20.3 x 17.8 cm

8,9,10: Principal Investigator and Co-Investigator Responsibility, Commitment, Relevant Scientific Experience and Biographical Information.

A brief summary of these items is given below. They are covered in much greater detail in the Management Section and in the Biographies/Bibliographies appearing at the end of the Technical Section. It is assumed that the data analysis and systems design will be shared among all nine investigators.

F.B. McDonald, Chief, Laboratory for High Energy Astrophysics, GSFC, and Professor of Physics (P.T.), The University of Maryland; studies of galactic and solar cosmic radiation and planetary magnetospheres; concerned with overall experiment design.

B.A. Randall, Assistant Research Scientist, The University of Iowa; magnetospheric research; responsible for the MTA detector development, fabrication and physical calibrations.

E.C. Stone, Associate Professor of Physics, Caltech, and Project Scientist, MJS; solar and galactic cosmic rays, energetic particles in the magnetosphere; Principal Investigator for this investigation.

J.H. Trainor, Associate Chief, Laboratory for High Energy Astrophysics, GSFC; research in cosmic radiation, trapped particles and electronics; responsible for management of MJU experiment.

J.A. Van Allen, Carver Professor of Physics and Head, Department of Physics and Astronomy, The University of Iowa; extensive research in planetary magnetospheres and cosmic radiation; responsible for the overall scientific and technical development of the MTA.

M.A. Van Hollebeke, Research Associate of the University of Maryland at GSFC; solar and galactic cosmic ray studies; responsible for HETS calibrations.

R.E. Vogt, Professor of Physics, Caltech, research on the astrophysical aspects of cosmic radiation; responsible for the LET and ELET detector design, fabrication and testing.

T.T. von Rosenvinge, Physicist, Laboratory for High Energy Astrophysics, GSFC; research in solar and galactic cosmic radiation; responsible for the HET system.

W.R. Webber, Professor of Physics and Director, Space Science Center, University of New Hampshire; galactic and solar cosmic ray studies; concerned with ELET design and calibration.

APPENDIX A1

ON THE NATURE OF THE URANIAN MAGNETOSPHERE

It seems virtually certain that in situ observation of the magnetic field of Uranus and of the energetic particles associated with the planet will be an investigation of great intrinsic interest and one that will provide important contributions to the generalized understanding of plasma physical phenomena on an astrophysical scale. There will also be significant implications with respect to the internal structure and physical state of the planetary body.

A1.1 RADIO EVIDENCE

Measured disc temperatures of Uranus in the wavelength range 0.33 to 11.3 cm lie between (105 ± 13) °K and (212 ± 17) °K, whereas the measured infrared temperature at 20 microns is (55 ± 3) °K. There is a reasonably convincing increase in radio brightness temperature from 0.33 to about 2 cm but no clear trend from 2 to 11 cm. The foregoing observations are generally considered attributable "to thermal emission by an atmosphere whose opacity is wavelength-dependent" (see review by Newburn and Gulkis, 1973).

If Uranus were endowed with the Jovian magnetic moment and the Jovian radiation belt of relativistic electrons and if the decimetric radiation therefrom were attributed to the disc of Uranus, its brightness temperature at 11 cm would be 6000 °K. The observed value at 11 cm is (160 ± 40) °K, insignificantly different from that at 2 cm. Hence, a Uranian radiation belt of relativistic electrons must be less effective than that of Jupiter as a radiator of synchrotron noise by a factor of the order of 200 or greater.

Recent observation of Uranus at 34.5 MHz (λ = 8.7 meters) places an upper limit of 8 Janskys (8×10^{-26} watt m^{-2} Hz^{-1}) on the continuum radiation (Shawhan and Cronyn, 1975). This upper limit is, however, far above that which would be observed in the synchrotron continuum at this wavelength from a Jovian radiation belt at Uranus. Also, during a cumulative observational period of 2 hours during 69 transits of Uranus no dekametric bursts were observed with power flux density exceeding the threshold sensitivity of 8 Janskys. Assuming analogous dekametric phenomena with those at Jupiter (Warwick, 1970; Carr and Gulkis, 1969), a much longer run of observations will be required to establish the presence or absence of dekametric burst activity at Uranus. It is, perhaps, more likely that burst activity will occur at lower frequencies as at Saturn (Brown, 1975) and the Earth (Gurnett, 1974), at frequencies below the cut-off of the terrestrial ionosphere and hence inaccessible to ground-based receivers.

Despite the foregoing "upper-limit" evidence, a Uranian radiation belt comparable to that of the Earth, for example, is not excluded by any existing observational data. There is no reasonable expectation that this state of ignorance will be dispelled by observations from the Earth or from spacecraft at ≈ 1 A.U. within the next ten to twenty years.

A1.2 MAGNETIC MOMENT

Table A1-1 summarizes the current state of knowledge of the magnetic moments of seven planetary bodies. All entries except the one for Saturn have come from in situ observations. The entry for Saturn has been inferred from the estimated upper cut-off frequency of the dekametric burst spectrum reported by Brown (1975). This upper cut-off of about 5 MHz was taken to be the electron gyro-frequency at the top of the planet's atmosphere, at high magnetic latitude. The analogous assumption for Jupiter yields an estimate of its magnetic moment within a factor of two or three of that derived from in situ observations. In fact, there is one high latitude region on the surface of Jupiter within which the magnetic field strength is 14 gauss (Smith et al., 1975), corresponding almost exactly to an electron gyro-frequency of 41 MHz, the upper cut-off frequency of the dekametric burst spectrum.

Broadly speaking there are five qualitatively different types of magnetism that a planetary body can exhibit.

(a) Remanent ferromagnetism in cool crustal material.

(b) Electromagnetism caused by electrical currents in an electrically conductive interior, such currents being driven by self-excited dynamo electromotive forces generated by convective flow of material. (This mechanism probably requires planetary rotation).

(c) Electromagnetism of type (b) at some remote epoch, with subsequent resistive-inductive decay of the current systems after the electromotive forces have become negigible.

(d) Electromagnetism caused by systems of electrical currents induced in the conducting ionosphere of the planet by fluctuating magnetic fields in the solar wind and/or driven by the unipolar induction electric field caused by the relative motion of magnetic fields in the solar wind as these fields are convected past the planet. (In the latter case the electrical circuit is closed through the conductive interplanetary medium.)

(e) Electromagnetism similar to type (d), but with currents in conducting portions of the planetary body itself.

Most of the interior volumes of all of the bodies in Table A1-1 (with the possible exception of the Moon) are thought to be at temperatures above the Curie temperature of ferromagnetic materials (≈ 1000 °K); hence, remanent ferromagnetism, if any, must be confined to the outer skins of the bodies.

In the framework of the above summary, the magnetic and magnetospheric properties of the several planetary bodies are thought to correspond to the listed types of magnetism as given in Table A1-2. For large, rotating planets having fluid interiors, there is no theory of type (b) magnetism which proceeds from first principles to a confident prediction of the gross magnetic moment of the planet. Nonetheless, it is noted from Table A1-1 that the ratios of the rotational angular momenta $I\omega$ to the magnetic moments M for the Earth, Jupiter, and Saturn satisfy the following inequality:

$$0.7 < \left(\frac{I\omega}{M} \times 10^{-15} \right) < 3.5.$$

Evidence for such an approximate constancy of the $I\omega/M$ ratio for astronomical bodies was noted by Blackett many years ago (1947; 1949). He suggested that this ratio might be a fundamental property of matter but later showed that this

TABLE A1-1

	$I\omega$ Rotational Angular Momentum (1) (2)*	M Magnetic Moment	$\frac{I\omega}{M} \times 10^{-15}$
	gm cm^2 sec^{-1}	gauss cm^3	gm $(sec\ cm\ gauss)^{-1}$
Mercury	9.60×10^{36}	5.1×10^{22} (3)(4)	0.19
Venus	1.82×10^{38}	$< 8 \times 10^{21}$ (5)(6)(7)	> 23.0
Earth	5.86×10^{40}	7.98×10^{25} (1)	0.734
Mars	1.98×10^{39}	2.4×10^{22} (8)(9)(10)	83.0
Jupiter	4.28×10^{45}	1.536×10^{30} (11)	2.8
Saturn	7.71×10^{44}	$\approx 2.2 \times 10^{29}$ (12)	≈ 3.5
Uranus	1.94×10^{43}	--	--
Neptune	2.08×10^{43}	--	--
Pluto	$\approx 4.7 \times 10^{38}$	--	--
Moon	2.34×10^{36}	$< 4 \times 10^{20}$ (13)(14)	> 5.9

*References are listed at the end of this Appendix.

TABLE A1-2

	Probable Type of Magnetism
Mercury	(a) and/or (e)
Venus	(d)
Earth	(b)
Mars	(a) and/or (e)
Jupiter	(b)
Saturn	(b)
Uranus	(b) or (d)
Neptune	(b) or (d)
Pluto	(a) and/or (e)
Moon	(a) and (e)

is probably not the case by experiments in deep mines in the Earth and by laboratory experiments. Even more persuasive evidence for the lack of validity of the Blackett hypothesis was noted by Van Allen et al (1965) on the basis of the measured upper limit on the moments of Mars and Venus (Table A1-1).

The "safe" point-of-view is that the magnetic moment of Uranus is totally unknown.

Nonetheless, empirical evidence gives some support to the rule-of-thumb that $I\omega/M \approx 10^{15}$ gm (sec cm gauss)$^{-1}$ for "sufficiently large bodies that are rotating sufficiently rapidly". In this crude framework, Venus may be characterized as being large enough but not rotating rapidly enough (244.3 day sidereal period); Mars, as rotating rapidly enough (24^h 37^m) but not being large enough; and the Moon and Mercury, as meeting neither criterion. Saturn, Uranus, and Neptune have rotation periods intermediate between those of Jupiter and the Earth and also have sizes, gross compositions, and internal pressures intermediate between those of Jupiter and the Earth.

In the spirit of the foregoing discussion, one may suggest, under peril of being quite wrong, that the magnetic moment of Uranus is $\approx 2 \times 10^{28}$ gauss cm^3 and the surface equatorial field is $\approx$ 1.4 gauss. Even if this conjectured value is too high by a factor of 100, there will very likely be magnetospheric phenomena at Uranus of high interest.

A1.3 SOLAR WIND AT THE ORBIT OF VENUS

The properties of the solar wind have been measured over the heliocentric distance range 0.31 A.U. (Helios) to 7.5 A.U. (Pioneer 10). Near the sun the solar wind velocity is strongly variable (150-1000 km sec^{-1}) with an identifiable relationship of high velocity and low velocity regimes to specific regions on the sun. With increasing radial distance, the range of variation diminishes but the mean value remains about the same, out to at least 5 A.U. (Collard and Wolfe, 1974). This mean value is $\approx$ 400 km sec^{-1}. The mean number density of particles is approximately proportional to the inverse square of the distance, as it must be for constant velocity and spherically symmetric expansion. Also in the range 0.3 - 5.0 A.U., the interplanetary magnetic field behaves in an essentially simple manner, with the magnitude of the radial component decreasing as the inverse square of the distance and that of the azimuthal component decreasing as the inverse first power (Smith, 1974). The radial dependence of these gross parameters as well as that of the more detailed parameters of the solar wind give no empirical foundation for estimating the position of the outer boundary of the directed flow of the solar wind, sometimes called the heliopause. A similar lack of foundation for such an estimate emerges from the lack of any increase of galactic cosmic ray intensity from 1.0 to 7.5 A.U. (Van Allen, 1975a). The most credible of current theoretical estimates (Axford, 1973) suggests a value of $\approx$ 50 A.U. as the radial distance of the heliopause in the direction of the solar apex.

At the orbit of Uranus (19 A.U.) it is therefore "reasonable", though of course perilous, to adopt values of the gross parameters of the solar wind as in Table A1-3.

TABLE A1-3

Adopted Solar Wind Parameters at the Orbit of Uranus

Velocity:	400 km sec^{-1} (relatively steady)
Number Density of Protons and Electrons:	0.014 cm^{-3}
Radial Component of Magnetic Field:	0.012 γ
Azimuthal Component of Magnetic Field:	0.22 γ
Angle of Mean Magnetic Vector to Radius Vector:	93° (+ sector) 273° (- sector)

A1.4 INTERACTION OF THE SOLAR WIND WITH THE MAGNETIC FIELD OF URANUS

(a) If, despite the simple-minded basis for Table A1-3, the radial flow of the solar wind ceases inside 19 A.U. and if the planet is unmagnetized, there will be only very weak magnetospheric phenomena at Uranus.

(b) If the radial flow of the solar wind ceases inside 19 A.U., but if the planet is magnetized, the physical situation will be that of a magnet rotating in a tenuous, nearly static plasma. Even in this case, however, there will be some relative velocity between the planet and the medium because of the 6.8 km $\sec^{-1}$ orbital velocity of the planet and the presumed 20 km $\sec^{-1}$ velocity of the solar system through the interstellar medium. By analogy with the best prevailing interpretation of the dynamics of the Jovian magnetosphere (Van Allen, 1975b; Gold, 1975), this low relative velocity will probably be sufficient to establish a significant axial asymmetry in the topology of the outer magnetic field and thus make it possible for internal processes to develop a body of magnetospheric phenomena, with the necessary energy being drawn from the rotational energy of the planet.

(c) The stand-off distance r of the magnetopause on the "windward" side of a planet having magnetic moment M is given by the magnetohydrodynamic stagnation condition

$$n\ m\ v^2 = M^2 / 2\pi r^6$$

where n, m, and v are the number density, mass, and directed velocity of protons in the plasma,

or
$$r = \left(\frac{M^2}{2\ \pi n\ m\ v^2} \right)^{1/6} .$$

Using the data of Table A1-3

$$r = 40.3\ M^{1/3}\ \text{cm}$$

or

$$r/r_U = 1.64 \times 10^{-8}\ M^{1/3}$$

with r_U = 24,500 km, the equatorial radius of Uranus, and M its magnetic moment in gauss cm^3. Examples are given in Table A1-4.

TABLE A1-4

Estimated Standoff Distances of
Uranian Magnetopause

M	r/r_U	
2.25×10^{23} gauss cm^3	1.00	
2×10^{25}	4.45	
2×10^{28}	44.5	("nominal")

If M is as small as 2.2×10^{23} (only 10 times as great as for Mars) or less, the magnetopause will be tangent to the top of the atmosphere in a manner resembling that at Venus. No magnetosphere containing durably trapped particles can exist. At the "nominal" value of 2×10^{28} gauss cm^3 a fully developed magnetosphere of large dimensions may be expected. Even if M is comparable to that of the Earth, a fully developed magnetosphere may be expected. If the velocity of the planet relative to the local plasma is as small as 20 km sec^{-1}, the stand-off distance $r/r_U = 16.4$ for $M = 2 \times 10^{28}$ or 1.64 for $M = 2 \times 10^{25}$.

A1.5 SPECIAL FEATURES OF A URANIAN MAGNETOSPHERE

The preceding discussion makes it appear quite likely that there are magnetospheric phenomena associated with Uranus.

A valuable review of the scaling principles of planetary magnetospheres has been given by Kennel (1973). He adopts as plausible a magnetic moment for Uranus of 1.9×10^{28} gauss cm^3 (cf. Section A1.3 above) and demonstrates that, in such a case, co-rotation effects will dominate diffusion effects and that a Uranian magnetosphere will have a closer physical resemblance to that of Jupiter than that of the Earth.

Uranus has a close regular system of five known satellites, all of whose orbits are accurately coplanar and nearly circular. The rotation period of the planet is not known accurately but the value $10^h 49^m$ is commonly adopted as being consistent with both photometric (cyclic variation of brightness) and spectroscopic (Doppler tilt of spectral lines across the visible disc) observations (Alexander, 1965). Measurements of the oblateness of the planet are exceedingly difficult but appear to be consistent with an axis of rotation perpendicular to the orbital plane of the satellites. A more persuasive argument to the same effect is based on the persistent coplanarity of the orbits of satellites I-IV over many years of observation. If the plane of the orbits were not coincident with the equatorial plane of the primary, the separate planes of the four satellite orbits would precess at different rates and coplanarity would be destroyed rapidly.

According to the Explanatory Supplement (1961), the inclination (J) of the orbital plane of satellites I-IV to the equator of the Earth and the right ascension (N) of the ascending node are

$$N = 166^{\circ}.051 + 0^{\circ}.0142 \, (t - 1900.0)$$

$$J = 75^{\circ}.145 - 0^{\circ}.0013 \, (t - 1900.0)$$

in which t is the Julian year. N and J are referred to the Earth's mean equator and equinox of date (t), the time-variable terms in the above expressions being attributable entirely to the precession of the earth's rotational axis (Duncombe, 1975).

The rotation axis of the planet is assumed to be perpendicular to the above plane, with its angular momentum (i.e., "north") pole south of the ecliptic plane by 8°.

A plot of the angle β between the axis of the planet and the planet-sun line is shown in Figure A1-1. The minimum value of β occurs in October 1985; β is less than 10° for an interval of 1000 days centered on this date.

No other planet has a rotation axis tilted more than 29° to its orbit plane. Thus, the extraordinary orientation of the rotation axis of Uranus makes it a planet of special interest for many types of investigations. The axis is nearly aligned with the planet-sun line in the years 1985 and 2027, whereas it is perpendicular to the planet-sun line in the years 2006 and 2048.

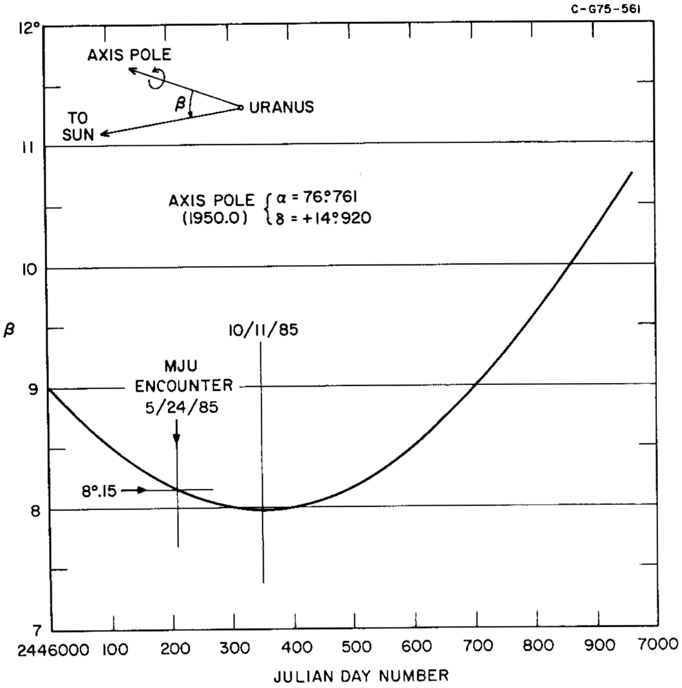
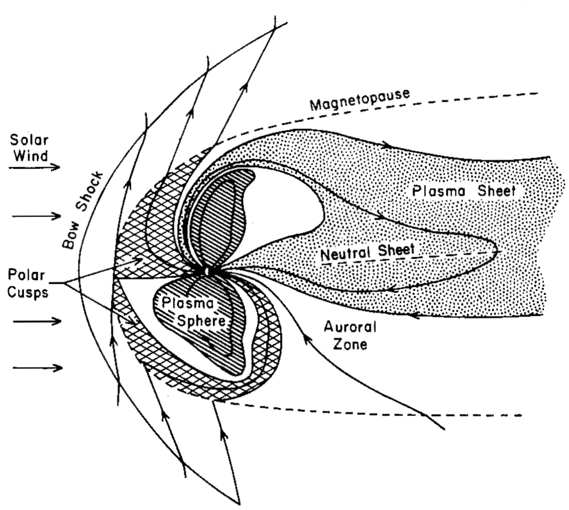


Figure A1-1

There is, as discussed earlier, no direct knowledge of the magnitude of the magnetic moment of Uranus, much less its orientation. If the magnetic and mechanical axes are approximately co-linear (as they are for the Earth and Jupiter) then the solar wind flow in 1985 will be also along the same line, whereas centrifugal forces will be perpendicular to this line. The physical nature of the magnetosphere of Uranus in this case has been discussed by Olson and more fully by Siscoe (1975). Figure A1-2 from Siscoe gives a schematic impression of the configuration expected.

If the magnetic axis is strongly inclined to the mechanical axis, then an even more exotic magnetosphere may be expected because of the large diurnal variation which will occur.

Also, it is likely that all five of the satellites will contribute particle sweeping and/or particle acceleration effects to the physical melee.



HYPOTHETICAL MAGNETOSPHERE OF URANUS
(AFTER SISCOE)

Figure A1-2

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APPENDIX A2

INTERPLANETARY OBSERVATIONS

A2.1 INTRODUCTION

In the low energy region (Protons and Electrons of 0.1 - 20 MeV) it has been generally assumed that the principal sources of the energetic particles observed in interplanetary space near 1 A.U. were solar particles and galactic cosmic rays. However recent observations of Explorers and Deep Space Missions have demonstrated there are a large number of additional sources including ejection from the magnetosphere of the earth, Jupiter and Mercury as well as what appears to be interplanetary acceleration processes. The properties of these new particle sources are still being explored. However it is expected that the particles themselves will act as large scale probes of the heliosphere. It appears that dynamic, large scale, astrophysical plasmas generally accelerate energetic particles. In this appendix some of the recent observations will be presented in greater detail. It is expected that as new regions of the heliosphere are explored, new processes will reveal themselves through their effect on energetic particles. For example, particles ejected from a Uranus magnetosphere would provide ideal probes of the outer heliosphere. As Vogt and Siscoe (1975) have emphasized, a new regime of plasma instabilities is expected beyond 10 A.U. in addition to the generation of large amplitude electromagnetic waves by neutral interstellar particle ionization in interplanetary space. There is every reason to believe that the outer heliosphere will be as rich in new energetic particle phenomena as has been observed at 1 A.U. For example, Fisk et al., 1974, have postulated that the ionization and acceleration of interstellar neutrals in this region could be the source of the recently discovered anomalous He, N, O and Ne. This is discussed further in Appendix A3. In this appendix Jovian electrons in interplanetary space and interplanetary acceleration processes are discussed in more complete detail. They are considered "typical" of the diverse interplanetary phenomena.

A2.2 JOVIAN ELECTRONS IN INTERPLANETARY SPACE

As Pioneer 10 approached Jupiter both the University of Chicago (Chenette et al., 1974) and the Goddard/University of New Hampshire experiments (Teegarden et al., 1974) observed low energy (~ 0.2 - 8 MeV) electron increases at ~ 1 A.U. from the planet. These discrete bursts or increases were typically several hundred times the normal quiet-time electron flux and became much more frequent as one approached Jupiter (Fig. A2-1). Close to Jupiter, but well outside its magnetosphere, there is the quasi-continuous presence of large fluxes of these electrons.

These observations suggested that Jovian electrons should be observable at 1 A.U. Previously it had been reported that the 3-12 MeV electron component detected by the IMP series (McDonald et al., 1972) frequently identified positive increases of these electrons that could not be associated with discrete solar events. These "quiet-time" increases represented a factor of

3-5 increase in intensity and lasted from 5-12 days. They displayed a remarkable anti-correlation with low-energy proton events and their amplitude was observed to generally diminish toward solar maximum. Reexamination of the IMP data revealed that these increases have a 13 month periodicity (Fig. A2-2), indicating a Jovian origin for the "quiet time" events observed near earth.

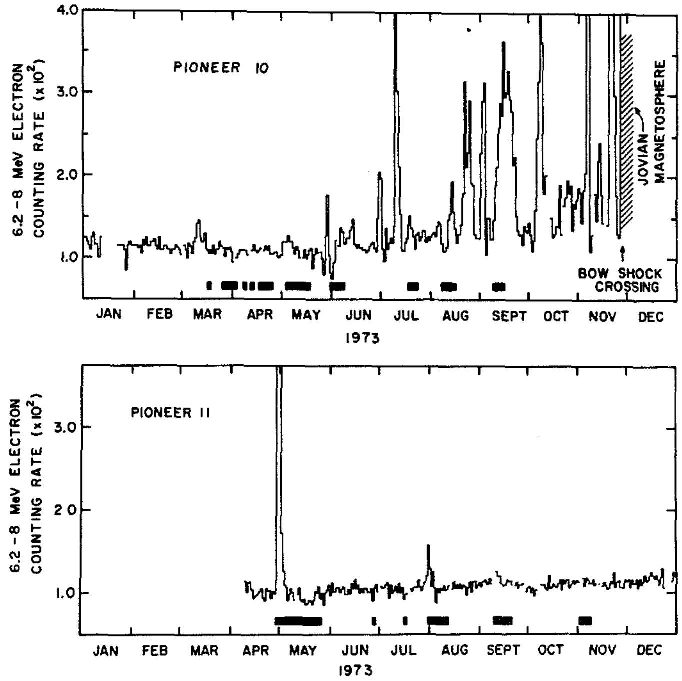


Fig. A2-1. The daily average counting rates for 6.2- to 8-MeV electrons on (a) Pioneer 10 and (b) Pioneer 11. The black rectangles indicate the larger solar cosmic-ray events. Most of these are of the low-energy corotating type. (After Teegarden et al., 1974)

In Fig. A2-3 the time of the year that the earth crosses Jupiter's field line is plotted for each year from 1964-1974. The vertical bars in the plot give the duration of the periods when the quiet time increases were present. With the exception of the 1964 bar, all the periods fall close to or contain the predicted time of crossing Jupiter's field line. This is a further indication that Jovian electrons are being detected at 1 A.U. Furthermore, the spectra of electrons observed in Jupiter's outer magnetosphere, in interplanetary space near Jupiter, for the quiet-time increases near the earth and for the ambient electron spectrum are all remarkably similar. These lines of evidence suggest that Jupiter is the source of most of the low energy electrons observed at 1 A.U. If we examine the entire electron energy spectrum (Fig. A2-4), it is seen that the entire low energy spectrum from 0.2 to 40 MeV is remarkably different from the relatively flat differential spectra measured from ~ 40 MeV to ~ 1 GeV. Above 1 GeV the measurements approach a power law of ~ E^{-3}. Since the spectral shape of the low-energy component is consistent with that of knock-on electrons produced in interstellar space by higher-energy nucleons, it has been generally assumed that they were interstellar secondaries. However, this model requires that the total solar modulation at low energies be less than a factor of ~ 5. The total solar modulation is the important question. This can be estimated by comparing simultaneous Pioneer and IMP data. In Fig. A2-5 daily averages are plotted for an 8 month period extending from December 1973 to July 1974. The sensitivity of the Pioneer data has been increased by using the pulse height information. It is readily seen that Jovian electrons are present for the entire 8 month period. The mid-December 1973 increase occurs essentially simultaneously at the 2 spacecraft. Using the known geometric factors and

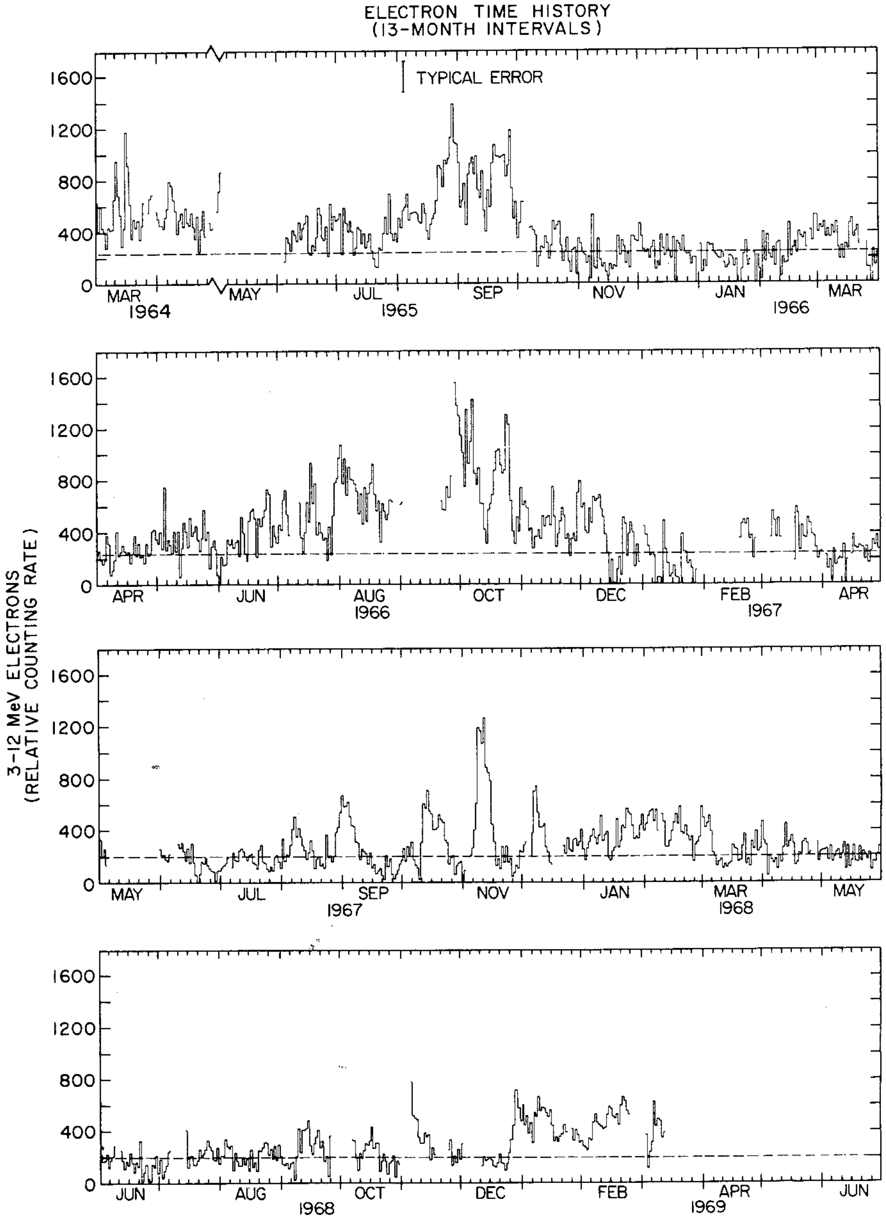


Fig. A2-2a. Imp 3, 4 (McDonald et al., 1972), and 5 (M. A. I. Van Hollebeke, private communication, 1974) 3- to 12-MeV data plotted in 13-month epochs, (a) from March 1964 to June 1969 and (b) from July 1969 to September 1972. The dashed line is a convenience for identifying the electron increases. There still may be major solar contributions in some periods such as July 28 to August 10, 1966, and September 20 to October 10, 1966. The 13-month periodicity is clearly defined, and the amplitude decreases over solar maximum (~1969). A background subtraction has not been made for the data after July 1969. (After Teegarden et al., 1974)

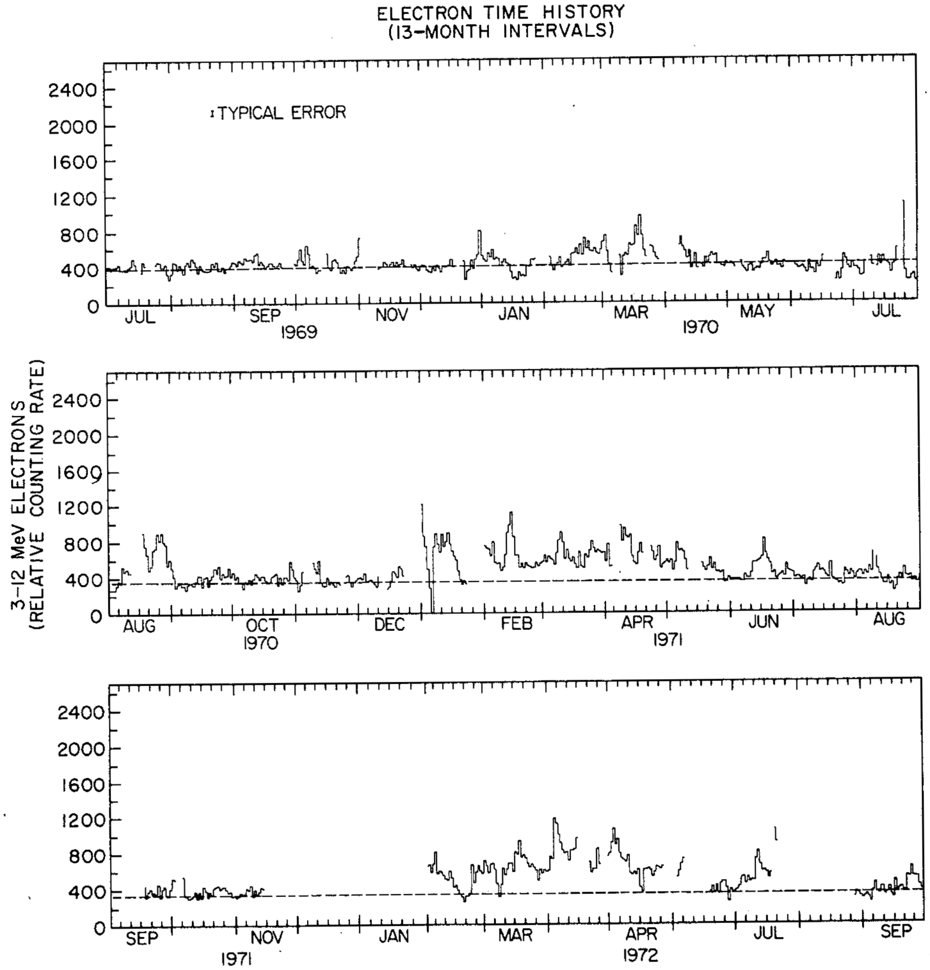


Fig. A2-2b.

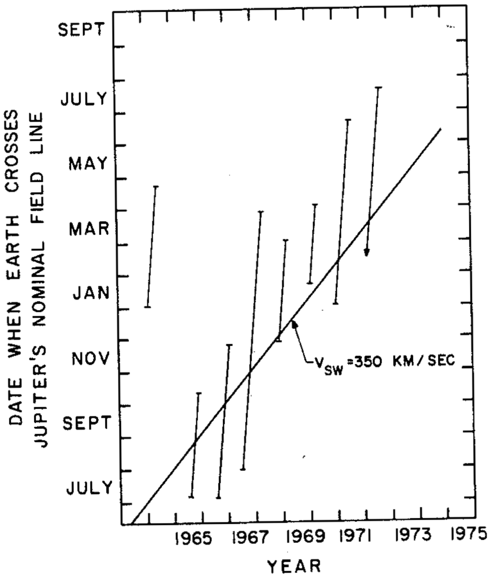


Fig. A2-3. The vertical bars give the duration of the periods when quiet time increases were present during the various epochs shown in Fig. A2-2. Arrows indicate when the length of the bar is uncertain owing to a data gap. The diagonal line represents the time of the year that an idealized spiral interplanetary magnetic field line would connect the earth and Jupiter, a constant plasma velocity of 350 km/s being assumed. (After Teegarden et al., 1974)

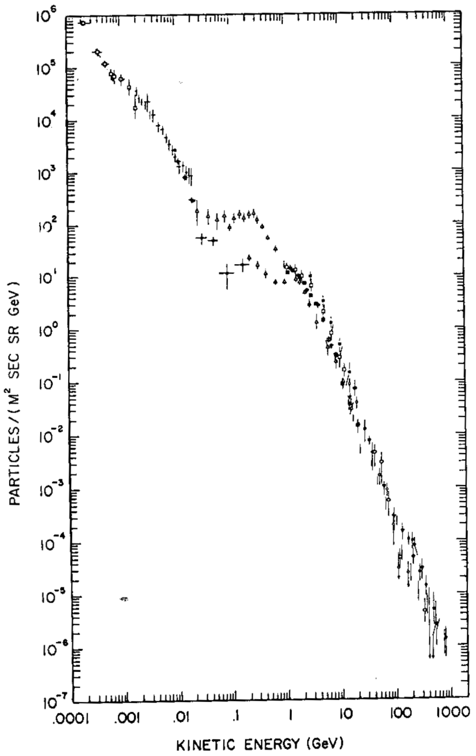
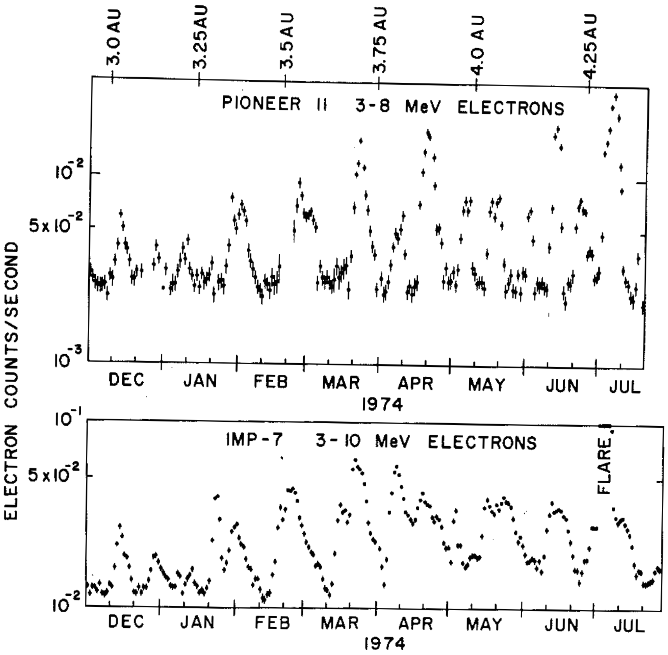


Fig. A2-4. Data on electron energy spectra from 0.2 MeV to 10^3 GeV. This represents the combined efforts of many different groups. The two data sets between 50 MeV and 1 GeV show typical solar cycle variations due to interplanetary modulation. The increase below 40 MeV may be largely of Jovian origin.

Fig. A2-5. Simultaneous observation of MeV electrons on Pioneer 11 and IMP 7. The sensitivity of Pioneer 11 has been extended over that of Fig. A2-1 by the use of pulse height information.



background response a gradient of ~ 150%/A.U. is found. In addition it is seen that the events become larger on Pioneer 11. It appears possible that the 0.2-40 MeV electrons observed near earth are mainly of Jovian origin. In addition it is expected that Jovian protons will be released at the same time. Their energy spectra are steep (T^{-4}) and in the Jovian outer magnetosphere they are generally ~ 1% of the electron flux at a given energy in the magnetosphere.

It is expected that Mercury should inject electron bursts into the interplanetary medium. Such activity has long been associated with the earth's own magnetosphere. In fact, the APL experiment on IMP's 7 and 8 shows that when the .3 - 1 MeV proton flux is at the lowest level, essentially all the nucleon flux is coming from the earth's magnetosphere. This ejection feature appears to be a general characteristic of planetary magnetospheres. With the far greater sensitivity of our MJU instrument (~ 30X that of Pioneer 10 and 11) it should be possible to map Jovian electron emissions out to very great heliocentric distances as well as identifying Uranian particle emissions when the spacecraft is very far from the planet.

A2.3 INTERPLANETARY ACCELERATION

Co-rotating streams of protons and electrons are the dominant type of low energy (i.e. ~ .1-10 MeV) event observed at 1 A.U. Their characteristics are significantly different from those of flare-associated increases. The rise and decay times are generally slower and more symmetric with little or no systematic velocity dispersion observed during the onset phase. They typically last for 4-10 days, suggesting widths of ~ 60-150° at 1 A.U. While there is no apparent correlation with solar flare and type IV radio emission, there is an association with increased geomagnetic activity, changes in the interplanetary medium, and with decreases in the galactic cosmic ray intensity. The energy spectra of the co-rotation events are sufficiently steep so that they are rarely detected above 20 MeV. In many cases the electron peak intensity (at ~ 40 keV) may occur several hours before the maximum proton flux. Multi-spacecraft studies indicate that transverse diffusion of particles across interplanetary magnetic field lines in these events appears to be negligible. A comprehensive survey of these events has been given by McCracken and Rao (1969). It was expected that these co-rotating streams would diminish rapidly with radial distance due both to adiabatic energy loss and spatial effects (Gleeson et al., 1971; Gleeson 1971).

The Pioneer 10 and 11 spacecraft with IMP's 7 and 8 at 1 A.U. provide an ideal means of studying the propagation dynamics of these co-rotating streams. The Pioneer trajectories are such that out to ~ 3 A.U. each spacecraft is within 25° of the nominal interplanetary magnetic field line intercepting the earth (assuming a plasma velocity of 400 km/sec). The first 3.6 months of data from Pioneer 11 along with that from IMP 7 is shown in Fig. A2-6 for 1.2 - 2.1 MeV protons. The initial agreement between the two data sets is quite good. This correspondence between the data sets remains reasonable until Pioneer 11 reaches 1.3 A.U. in June 1973 when there is an increase at Pioneer 11 on June 5 that is a factor of ~ 12 larger than at IMP. This data set certainly reveals no systematic decrease in the intensity of the co-rotating streams as had been predicted. To study the behavior of the streams at greater heliocentric distances, the same Pioneer 11 and IMP 7

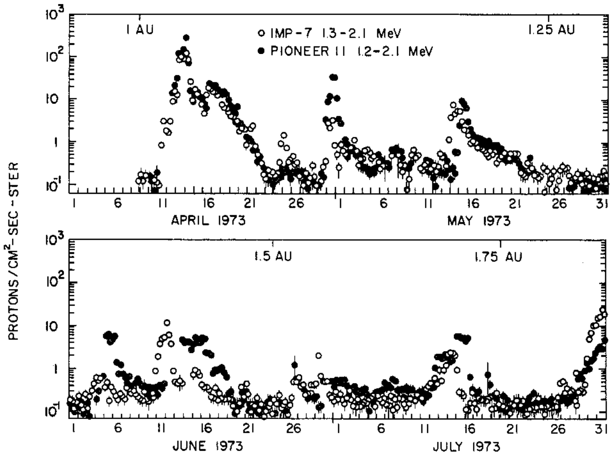


Fig. A2-6. Simultaneous 1.2-2.1 MeV data from essentially identical detectors on IMP 7 and Pioneer 11. The events in mid-April and late July are flare associated ones. The remainder appear to be co-rotating particle streams.

energy intervals are shown in Fig. A2-7 for the six month period from 1 November 1973 to 1 May 1974 during which Pioneer 11 moved from 2.68 to 3.94 A.U. The Jovian electron data indicates the co-rotation time between the two spacecraft was less than 1 day in mid-December and was on the order of 5 days in early April. Notice that the flare-associated increase on November 2, 1973 is reduced by a factor of 50 between IMP 7 and Pioneer 11.

The remaining 14 particle increases in this 6 month period which have peak fluxes at Pioneer 11 > 1 proton/cm^2-sec-ster-MeV appear to be co-rotating streams. Three of these have approximately the same peak intensity at both spacecraft (within ± 25%), 10 are larger at Pioneer 11 and 1 is larger at IMP. In most cases the Pioneer 11 events are larger by a factor of 10 to 20. This large increase in intensity is remarkably different from the conventional expectations that adiabatic energy loss processes associated with convection processes in the expanding solar wind would reduce these streams to negligible proportions by 3 A.U. The solar wind transit time between 1 and 3 A.U. is on the order of 10 days and the co-rotation delays are 1-5 days.

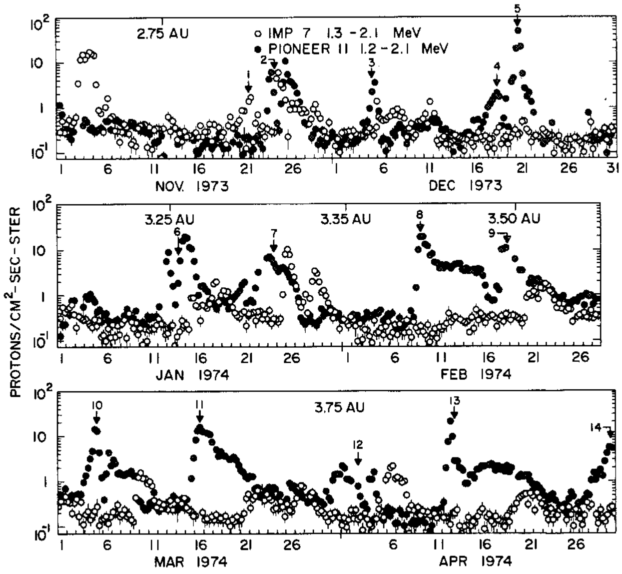


Fig. A2-7. This is a similar data set to that of Fig. A2-6 for the period when Pioneer 11 is between 2.7 and 3.8 A.U. Despite the relatively rapid rise time of many of the Pioneer 11 increases, there is no evidence for any velocity dispersion. Only the event in early November appears to be a flare-associated one.

Significant temporal variations in the structure of these streams could be expected over these times. Nevertheless, over more than six solar rotations, there is only one case where the streams are substantially larger at 1 A.U. than at 3-4 A.U. As emphasized earlier, new effects could be expected and have been predicted for the outer heliosphere.

Using the data from Zond 3 and Venus 2 during the 1965-66 period, Vernov et al., 1970, found a positive gradient of > 200%/A.U. for 1-5 MeV protons. They considered this may occur when the interplanetary magnetic field at great distance from the sun "becomes chaotic and the process of proton accumulation takes place." In the same paper the authors note the frequent association of co-rotating streams with Forbush decreases and raise the possibility that the 1 MeV protons are accelerated by the inhomogeneties of the solar wind.

It is necessary to establish that these increases are not of Jovian origin. The dramatic increases in MeV Jovian electrons seen on Pioneer 10 and 11 are not observed for protons. Some Jovian proton increases have been reported (Simpson et al., 1975; Trainor et al., 1975) but they are smaller and much less frequent than the electron increases. Furthermore, an anti-correlation has been established between co-rotating proton streams and Jovian electron increases seen at 1 A.U. (McDonald et al., 1972). A direct comparison between the Pioneer 11 flux of MeV electrons and the flux of protons for the six month period extending from December 1973 - 1 May 1974 shows no apparent correlation between the two sets of increases (Fig. A2-8). Thus, there appears to be no convincing evidence at this time to support a Jovian origin for these particles.

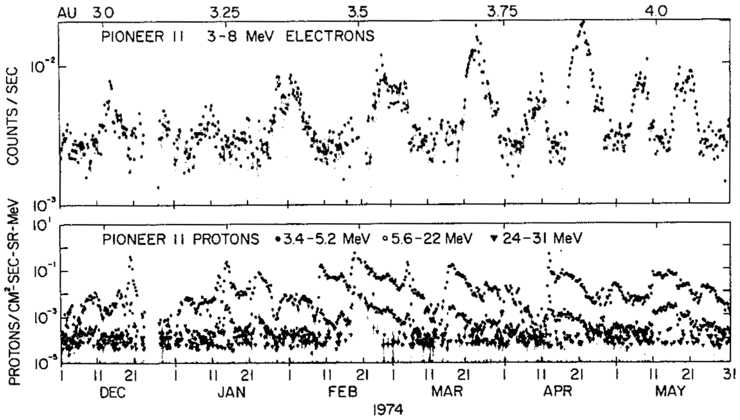


Fig. A2-8. Comparison between the Pioneer 11 MeV proton and electron data for the period December 1973 to June 1974. There are no obvious correlations between the Jovian electron increases and the co-rotating proton streams. The dynamic behavior of both types of events is clearly evident.

The most plausible hypothesis available to explain the growth of these proton streams is interplanetary acceleration. Several forms of interplanetary acceleration have been studied in the past. One, particle acceleration by interplanetary shock waves, is reasonably well understood (see for example Sarris et al., 1974). There may be a standing shock between slow and fast solar wind regions and this could play a role in the present observations. A second possibility has been suggested by Jokipii (1971) and Wibberenz and Beuermann (1971) who demonstrated that second order Fermi acceleration could be an important process of low energy solar particles in the interplanetary medium. This was originally considered to explain the observations of Murray et al., 1971, that the proton energies for a small flare event were decaying with a time-constant much longer than expected from adiabatic decelleration. Invoking magnetic irregularities moving in both directions along interplanetary field lines, with the Alfven velocity V_A, Jokipii obtained the following expression for the rate of Fermi acceleration:

$$\frac{1}{T}\frac{dT}{dt} \approx \frac{8\, V_A^{\,2}}{3\, K_{11}} = \frac{2\, B^2}{3\pi\, n m_p K_{11}} = \frac{1}{\tau_F}$$

T = Particle kinetic energy

K_{11} = Parallel diffusion co-efficient

B = Magnitude of the interplanetary magnetic field

n = proton density of the solar wind

m_p = mass of the proton

τ_F = characteristic acceleration time

Taking $K_{11} = 5\times10^{19}\,\mathrm{cm}^2$-sec (Jokipii, 1971), $n = 4$ protons/cm^3, $B = 10^{-4}$ gauss gives $\tau_F \approx 44$ hours.

Competing with this effect is adiabatic cooling given by

$$\frac{1}{T}\frac{dT}{dt} = -\frac{2}{3}\,\vec{\nabla}\cdot V = \frac{1}{\tau_{ad}}$$

For spherically symmetric expansion and $V = 500$ km/sec, $\tau_{ad} \approx 60$ hours. These estimates indicate τ_F and τ_{ad} can be of the same order.

Preliminary examination of the plasma data at 1 A.U. reveals that most of these co-rotating increases are associated with increases in the plasma velocity. The presence of slower speed solar wind streams may inhibit the free expansion of the higher speed region and reduce the effect of adiabatic energy loss although there is no evidence in the particle data to support this. This stream-stream interaction also establishes a turbulent interface region which could supply the magnetic irregularities for accelerating the particles. Belcher and Davis (1971) have shown this interface region is where Alfven discontinuities are largest and where it appears most probable that they are bi-directional along the field lines. Further studies are necessary to confirm that interplanetary Fermi acceleration is an important process and whether it is principally a first order process associated with shock fronts or whether it is second order as proposed by Jokipii. The presence of large field-aligned anisotropies (Krimigis et al., 1971) may be difficult to explain by this process and the value of K_{11} at low energies is not well known.

These processes raise the possibility that some co-rotating particle increases originate from the suprathermal distribution in the solar wind and are not accelerated at the sun. This, of course, is a speculative observation on which some light may be shed by the Helios and MVM energetic particle experiments, as well as by observations of the charge composition of these events.

The dynamic and ever-present nature of these two processes - Jovian emission and interplanetary acceleration - is clearly revealed in the data of Fig. A2-8. There is now very preliminary evidence beyond Jupiter of cross-coupling between the two processes and the resulting further acceleration of the Jovian electrons. The MJU experiment with the extended low energy coverage of the MTA is ideally suited to further study this as well as new processes. The charge composition capabilities of the ELET should also provide an important diagnostic tool for identifying the nature of the various acceleration processes.

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APPENDIX A3

CHARGE AND MASS SPECTRA OF THE GALACTIC COSMIC RAYS

A3.1 INTRODUCTION

Cosmic-ray astronomy is the study of charged particles which are accelerated in the most energetic of astrophysical plasmas and whose composition is directly related to the synthesis of matter of which the earth and sun are made. The acceleration process creates particles whose energies span the range from at least 10^6 to greater than 10^{20} eV. All nuclei that are contained in the periodic table of the elements as well as electrons and positrons are present in the galactic cosmic radiation.

The great interest in these particles comes from the fact that they are the only sample of stellar matter that reaches us directly from outside the solar system and their composition can be determined with much better precision than any other extra-solar distribution. As such, they provide a probe for studying a number of major questions in astrophysics. In particular, the charge and mass spectra should reveal the nature and history of the source regions. Many other fundamental questions can be answered by careful analysis of one or several essential particle parameters; for example:

1. What processes of nucleosynthesis create the material in the cosmic ray source region? This can be answered by studying the charge and isotope composition over a wide range of energy.

2. What mechanisms accelerate the galactic cosmic rays? Does the acceleration take place during or after nucleosynthesis? Energy spectra and isotopic composition as a function of energy will provide a solution.

3. How far have the cosmic rays travelled, and how do they propagate in the interstellar medium? Such questions have been partly answered by measuring the abundances and energy spectra of selected elements such as the light L nuclei: Li, Be and B. This has been possible because nuclei in this group are unlikely to be produced by the primary nucleosynthesis process and can only stem from fragmentation of heavier nuclei and collisions with matter as they propagate through the galaxy. This work can be greatly inproved upon by the study of isotopes. For example, the cosmic ray lifetime can be determined by the measurement of unique radio-isotopes such as ^{10}Be which represent radioactive "clocks."

4. The recent discovery of anomalous oxygen and nitrogen enhancements below 30 MeV/nucleon (McDonald, et al., 1974) suggest that the nature of the low energy (<50 MeV/nucleon) cosmic rays is very different from that observed at higher energies. Are there new sources of cosmic rays at these energies?

To fully answer these questions it is of first importance that measurements be made over an extended range of energy and at sufficiently large distances such that modulation and adiabatic energy loss effects are unimportant.

In this appendix we review briefly what is known of the charge and mass composition and attempt to highlight where important new advances can be made.

With the steady improvement of detector systems and the availability of balloon and satellite missions, there has been a dramatic increase in our understanding of the primary cosmic-ray charge composition at 1 AU. The picture that has clearly emerged is that the composition changes significantly from one energy regime to another.

A3.2 ELEMENTAL ABUNDANCE

The observed relative abundance of the elements at medium energy (∿.2-1 GeV) can be regarded as being well determined at least up to Silicon since most of the observations with good statistical weight show rather good agreement. The present knowledge of the abundance distribution of the elements in the range from a few hundred MeV/nucleon to about 1 GeV/nucleon for Oxygen to Iron is summarized in Fig. A3-1. This charge spectrum is composed of a mixture of "primary" nuclei that can be assumed to have originated in the source and "secondary" nuclei produced by fragmentation of heavier nuclei during their travel through the interstellar medium or other matter. For comparison, the so-called "solar System: abundances (SS) are also shown in Figure A3-1. This distribution is intended to represent the cosmic abundance of the vast majority of matter in the universe and such a comparison can yield interesting results on the origin of the galactic cosmic ray elements.

These two distributions show striking similarities, particularly the abundance maxima at carbon and oxygen and at the iron group. From C onward, there is a pronounced enhancement in both distributions of even atomic number nuclei compared to those of odd atomic number (Z). A few differences may also be noted: The light elements Li, Be and B are over-abundant by some four or more orders of magnitude in comparison with corresponding solar system abundances. The nuclei between phosphorus and chromium (Z = 15 - 24) are also enhanced. Their presence in the cosmic rays can be understood as being due to fragmentation in the nuclear interactions of heavier cosmic ray nuclei with ambient matter during the propagation of the cosmic rays from their source to earth. Extensive studies of the fragmentation of cosmic ray nuclei such as CNO to Li, Be and B have contributed to a large extent in formulating models of interstellar propagation. At this point, the phenomena of propagation can be considered as sufficiently understood to make first-order extrapolations to the source region. It is found that He, H, C, O, Ne, Mg, Si, Fe and Ni are definitely present in the cosmic ray sources. For these elements the observed fluxes represent ∿80% of the source abundance. The abundances of N, Na, Al, S, Ar, Ca, Cr and Mn are not so well known and possibly 50% of the observed abundances represent interstellar secondaries. The ratios of the best known of these cosmic-ray source abundances to the solar system abundances (CRS/SS) have already produced interesting results concerning nucleosynthesis processes. However, interpretations such as production of all cosmic rays by explosive nucleosynthesis (Silberberg et al., 1973; Kozlovsky and Ramaty, 1973) are not shared by all authors and there is a need for better

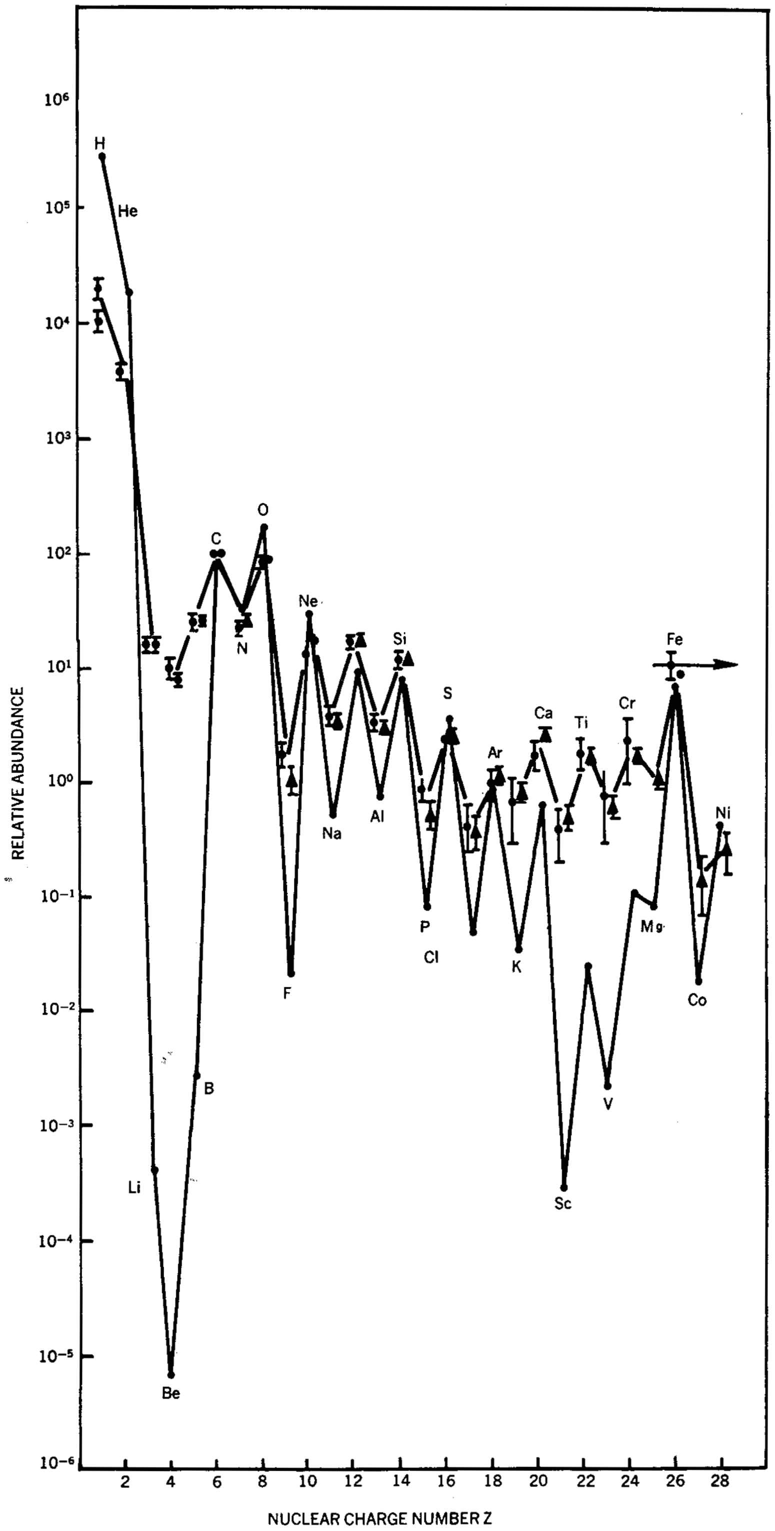


Figure A3-1

Relative abundances of the elements from Hydrogen to Iron normalized to carbon (C = 100). The closed circles without error bars represent the element abundances in the solar system. They are joined with a light line. Different symbols for the cosmic-ray abundances measured near earth present results from different experiments.

knowledge of the abundances particularly for the second group and as a function of the energy.

A3.3 ENERGY SPECTRA

The energy spectra of individual species over a wide energy range are important for determining the dependence of the cosmic-ray composition on particle energy. In Figure A3-2 the spectra of the more abundant nuclei such as H, He, C+O and iron are presented. All these spectra are well described by power laws in total energy $\frac{dJ}{dE} \propto E^{-\gamma}$ at energies high enough to avoid major influence from the interplanetary medium. Below 1 GeV, studies at the Earth are more difficult to interpret and the spectra deviate from simple power laws. For example, the differential spectra shown in Figure A3-2 increase slower with decreasing energy, reach a maximum at a around a few hundred MeV/nucleon and then decrease at still lower energies. Moreover the spectral shape is not the same for all components. Changes in the spectra are the result of the combined effects of solar modulation, energy loss in the interstellar space during propagation and, perhaps, of differences in the source spectra. Effects of solar modulation are seen in the different curves which for the same species correspond to measurements made at various levels of solar activity.

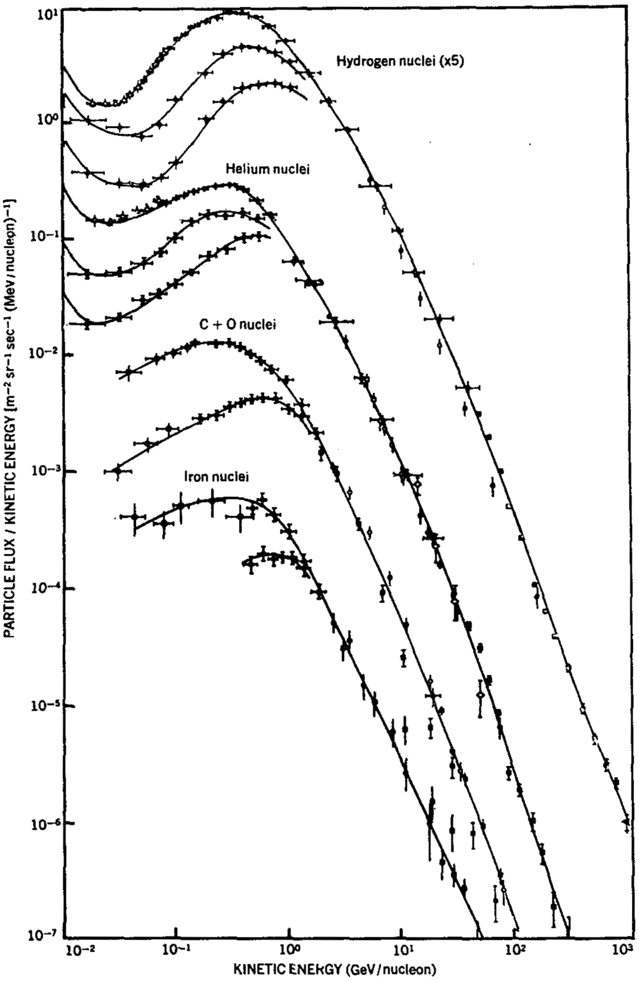


Figure A3-2: Cosmic-ray energy spectra of the more abundant nuclear species as measured near earth. Below 1 GeV these spectra are strongly influenced by modulation within the solar system.

Effects of ionization during propagation in interstellar space are a function of $\frac{Z^2}{\beta^2}$ and become important at low energy. In Fig. A3-3 these effects are shown as an example for protons, oxygen and iron, assuming the same power law spectra at injection and using two different models: (a) the steady-state model assumes that the galaxy is filled with sources whose average emission is constant and that there is a finite leakage of cosmic ray particles from the volume that contains the majority of these particles; (b) the slab model (dotted curves) assumes a simultaneous production with all particles traversing the same amount of material. It can be readily seen that major information on the propagation, source distribution, and acceleration of those nuclei are contained in their spectral shapes. Inside the modulation boundary, however, these effects are completely obscured by solar modulation processes.

A3.4 ISOTOPES

In addition to the use of the radio-isotopes as chronometers to measure the age of the cosmic radiation, the relative abundances of the stable isotopes such as ^{2}H and ^{3}He are used to provide information on the propagation and origin of the particles. This information is deduced from the differences we can observe with respect to the solar system abundances. At this moment, progress is just starting to be made on the isotopic abundances of the galactic cosmic rays. There now appear to be consistent measurements of ^{2}H and ^{3}He, and the University of Chicago has achieved resolution of ^{6}Li, ^{7}Li, ^{7}Be, ^{9}Be, ^{10}B and ^{11}B. However, because of uncertainties in the modulation process it is difficult to assign a primary energy to these observations. There also exist difficulties due to the lack of statistics and the poor resolution which have prevailed in the past. With the new generation of good resolution systems which started with IMP's 7 and 8, which have since been improved for MJU, and with an environment free of solar effects, great progress is expected.

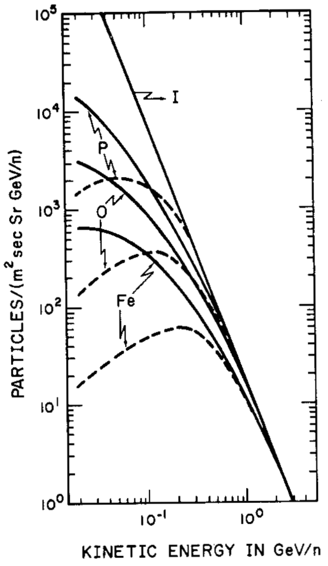


Figure A3-3: Effects of ionization during propagation are shown using a steady-state model (solid curves) and a slab model (dotted curves) for a power low at injection (Curve I). Curves P, O and Fe are for protons, oxygen and iron nuclei, respectively.

For example, secondary isotopes are produced by fragmentation of heavier nuclei during propagation. The relative abundance of each isotope is determined by the production cross sections and the path length distribution of the progenitors. Both of these factors can be energy dependent and thus the isotopic ratios will show energy dependent features that will provide information on the energy at which the nuclei are formed and this will show whether acceleration or energy losses play an important role.

Primary isotopes reflect the conditions in the sources where almost nothing is known. Most of the preliminary reports of isotopic cosmic ray abundances have suggested larger abundances of rare isotopes than those of the solar system. If confirmed, this may reflect interesting effects.

A3.5 ANOMALOUS ABUNDANCES OBSERVED AT LOW ENERGY

Some of the most fascinating and least understood data on cosmic ray composition has been reported at low energies (below a few tens of MeV/n). In this region, the presence of solar produced particles must be expected and one of the most important questions is whether the particles observed are solar or extra-solar in origin.

Until recently the only data at these low energies were those on hydrogen and helium nuclei. It was observed that even during the solar "quiet times" proton and alpha spectra exhibit a minimum in the 15-20 MeV/nucleon region and a steep negative slope (turn-up) at lower energies (Fan et al., 1968). The low energy component is generally highly variable and Kinsey (1970) has shown that it is dominated by particles of solar origin. However, at the lowest quiet-time levels at solar minimum, Fan et al. (1968) found a distinctive and reproducible turn-up measured during 1964. More recently, in 1972 near the next solar minimum with considerable improvement in the experimental techniques available, the general features of a sharp turn-up at low energy appears to be confirmed although the question of the energy at which it occurs is controversial. In particular, the helium spectrum remains flat to appreciably lower energies.

It is tempting to assume that the rapid increase represents a solar component superimposed on a nearly flat spectrum of galactic particles that must be present at these times of solar minimum. However, galactic origin for all the particles cannot be ruled out and the flat He spectrum does appear to be anomalous.

In these energy ranges, new results are just beginning to be available on the abundance of the heavier nuclei, especially C, N and O. Previous attempts at such measurements in the past were afflicted with poor statistical weight, large detector background, and inadequate charge resolution as well as difficulties due to solar contamination. On IMP 7 and Pioneer 10, part of the above difficulties were overcome. Observations using 260 days of quiet-time data were reported (McDonald et al., 1974) both on the Helium spectrum and the abundance of C, N and O nuclei at low energy. Those results are shown in Figure A3-4 (see Page A3-7) with the still-lower energy spectra reported by Hovestadt et al. (1973). The most unexpected feature is the anomalous charge composition seen at those energies: At about 10 MeV/nucleon Oxygen and Nitrogen are about 10 times more abundant than carbon, whereas O/C and N/C are comparable in the solar and (higher-energy) galactic cosmic rays. Except for a second turn-up below 1 MeV/nucleon which is presumably solar in origin (Hovestadt et al., 1973) those nuclei are unlikely to be of solar origin. Various groups have subsequently verified these results. It has become evident that they cannot, at present, be understood in terms of interstellar propagation or solar modulation effects without involving a new component having a different composition. On the other hand, based upon observations of very low ratios of ^{2}H and ^{3}He to ^{4}He, Teegarden et al. (1975) have concluded that there must be a nearby source of low-energy helium. Similar conclusions based upon the spectral shape of helium compared to that of other nuclei with the same $\frac{A}{Z}$ have been reached by Garcia-Munoz et al. (1975). Von Rosenvinge and McDonald (1975) have just measured for the first time a low-energy turn-up in Ne and have concluded that this turn-up is not of solar origin.

These very recent results on anomalous abundance are indeed puzzling. As an alternative model Fisk et al. (1974) have proposed that the helium, oxygen and nitrogen are interstellar neutrals which become ionized and accelerated in the interplanetary medium while interstellar carbon, presumably not neutral, will be excluded from the solar cavity. This model presents, however, some difficulties in that (1) it postulates an "ad hoc" acceleration mechanism placed beyond observation in the outer solar system so that both acceleration and solar modulation may occur; (2) it requires a large amount of energy from the solar wind: (3) there is limited knowledge of which of the nuclei are neutral in the interstellar medium. However, this model did predict that Neon, as one of the nuclei with a first ionization potential greater than that of neutral hydrogen, should be enhanced.

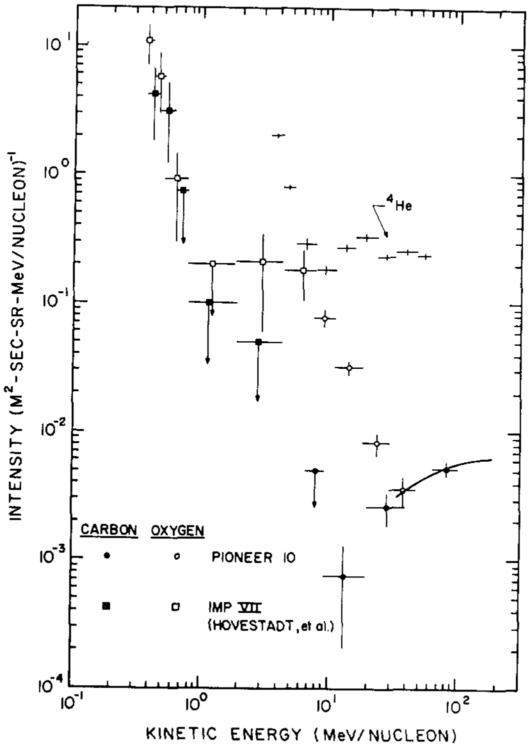


Figure A3-4: C, O and ^{4}He spectra. The C and O spectra at higher energies derived from the GSFC telescope on IMP 7 are indicated by the solid line. Note the flat spectrum of ^{4}He and the anomalous abundance of O relative to C between ∿2 and 30 MeV/nuc.

A3.6 CONCLUSION

The experiment described in the main body of the proposal will resolve individual elements from Hydrogen through Iron over an energy range extending from ∿0.5 MeV/n. to 500 MeV/n. It will resolve individual isotopes through Oxygen. Such a detector system will be able to take full advantage of the opportunity to make cosmic-ray observations beyond the boundaries of the cosmic-ray modulation region. As we have tried to emphasize in this appendix, many important cosmic-ray phenomena are almost completely obscured by adiabatic energy loss. This process removes all knowledge of the low-energy cosmic ray spectra, the effects of energy loss by ionization in the interstellar medium and precise knowledge of the cosmic ray lifetime. It is vital that in situ measurements be made of these important quantities. This can only be realized with a deep-space probe such as MJU.

APPENDIX A4

INTERSTELLAR COSMIC-RAY STREAMING ANISOTROPY

One of the most exciting aspects of an MJU-type Outer Solar System Mission will be the very real possibility of the spacecraft's escape from the solar system modulation region for cosmic rays; i.e., we will have the chance to study galactic cosmic rays free from the influence of the sun. A particularly powerful tool in the study of the interstellar phenomena will be the measurement of cosmic-ray streaming anisotropies.

A4.1 STREAMING ANISOTROPIES OF INTERSTELLAR COSMIC RAYS

Observations of interstellar anisotropies from Earth have so far been frustrated by experimental difficulties. Such a determination is in principle possible only for energies $\gtrsim 10^{12}$eV, because at lower energies the irregular interplanetary magnetic field mixes and randomizes the particle trajectories to such an extent that reconstruction of an anisotropy outside the solar wind is impossible. In addition, the anisotropies are expected to be very small, in view of the large sampling volume at high energies. At present, therefore, any attempt to estimate the anisotropy of the bulk of cosmic rays ($E \sim 10^9$eV) is sheer speculation.

In situ measurements of galactic cosmic-ray streaming on outer solar system missions, particularly outside the modulation region, are essentially free of solar perturbations, and can be performed at low energies where, in view of the ionization-loss limited pathlengths, the largest effects may be expected.

Consider the following illustrative example: Let a particle propagate locally by diffusion, with diffusion coefficient parallel to the B-field,

$$K_{\parallel} = \frac{1}{3} \lambda_{\parallel} w$$

where $\lambda_{\parallel}$ is the scattering mean free path and w the particle speed. If U is the cosmic-ray density, the streaming of cosmic rays is given by

$$F = -K_{\parallel} \frac{\partial U}{\partial Z}$$

where the magnetic field is in the z-direction. The associated anisotropy then is

$$\delta = \frac{3F}{wU} = - \frac{3K_{\parallel}}{w} \frac{1}{U} \frac{\partial U}{\partial Z} \approx \frac{\lambda_{\parallel}}{L}$$

where $L = (\frac{1}{U} \frac{\partial U}{\partial Z})^{-1}$ is the scale variation of U. L and $\lambda_{\parallel}$ are parameters of the interstellar medium. Consider particles at low energies (e.g., protons of $\sim$1 MeV) coming from a nearby source at a distance of the particles' range (set by ionization loss), $L \gtrsim 200$ pc. With a diffusion mean free path

$\lambda \approx 30$ pc we would observe an anisotropy of $\delta = \frac{\lambda}{L} \approx 15\%$, which is most easily measurable!

If, on the other hand, local diffusion should not be the mode of particle transport in the galaxy, some general considerations still hold. Particles streaming along field lines would be expected to show significant anisotropies. Particles produced in the galaxy and restricted to an apparent leakage lifetime of $\tau \sim 10^6$ years, will produce a general convective anisotropy of the order of

$$\delta \approx \frac{3V}{w}$$

where the required mean particle bulk speed $V = \frac{L}{\tau}$ is determined by the length of a typical line of force $L \approx 300$ pc and the lifetime $\tau \approx 10^6$ years; i.e., $V \approx 0.001$ c, which for 10 MeV ($\beta \approx 0.14$) protons results in an anisotropy of

$$\delta \sim 2\%$$

which is within the sensitivity of our instrument.

A4.2 INTERSTELLAR COSMIC RAYS: STREAMING AND SOURCE IDENTIFICATION

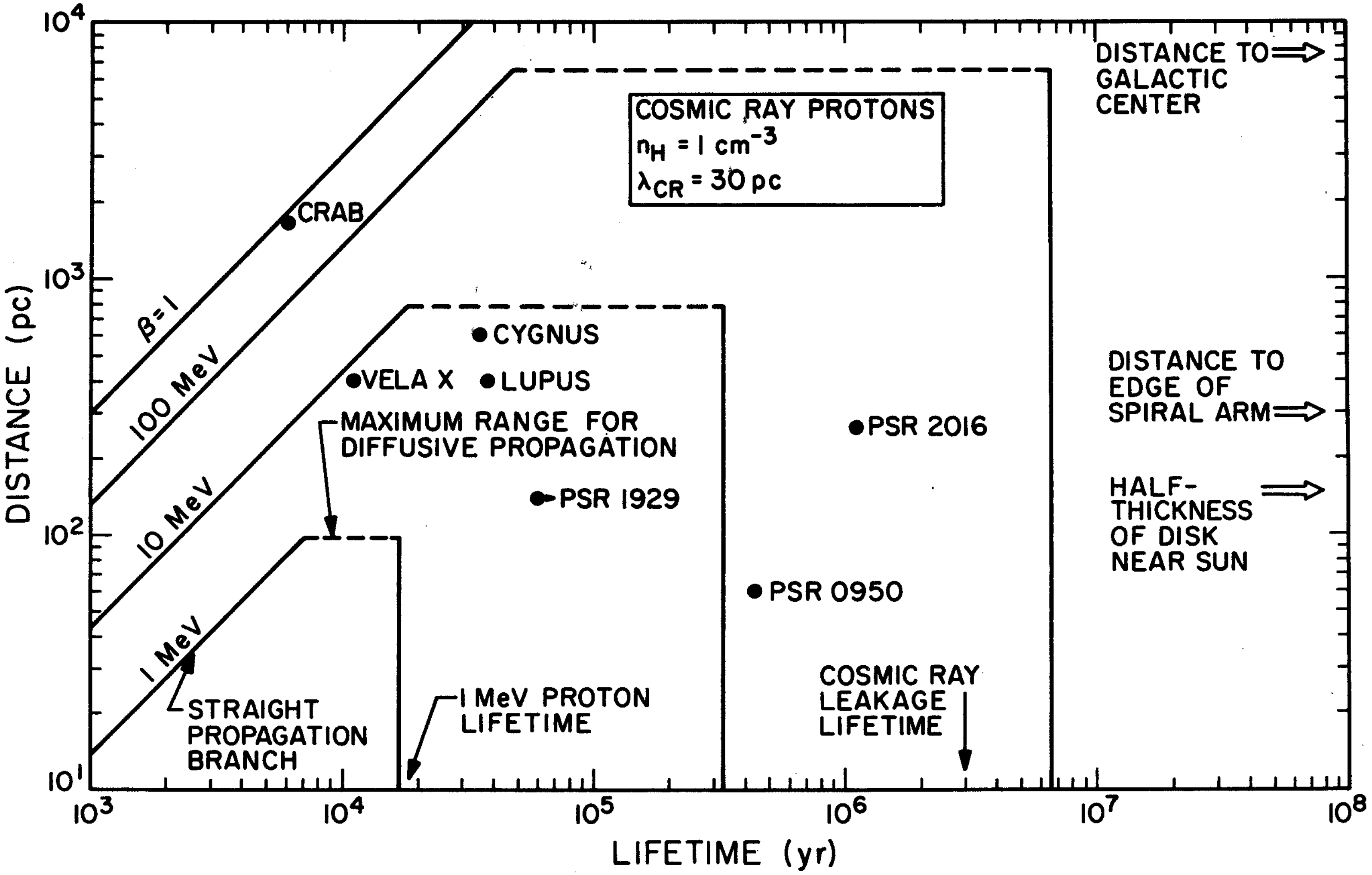
In situ measurements of cosmic ray fluxes in the interstellar medium, i.e., outside the solar modulation region, represent a powerful new tool in the study of astrophysical phenomena. In particular, the *complete* determination of both the isotropic component and the streaming vector $\vec{S}$ (anisotropy) of the cosmic ray flux, as provided by the proposed LET telescope system, will greatly aid the analysis of interstellar particle propagation phenomena and the associated field, matter, and energy parameters of the interstellar medium. One of the most exciting products of the measurement of cosmic ray anisotropies may be the direct identification of a specific astrophysical object, e.g., a pulsar or supernova remnant, as the source of an identified component of the observed cosmic ray flux. Such identification of discrete cosmic ray sources with their ejecta would be of profound significance, since it would provide us with direct material samples from these rather mysterious objects which are under intensive investigation by a large multidisciplinary group of today's astrophysicists.

Source identification will be attempted from the measurement of the interstellar streaming patterns and the energy spectra of low-energy cosmic rays over an elemental domain ranging from hydrogen through iron. As shown in Section A4.1, the anisotropies are expected to be most pronounced (in the order of tens of percent) in the low-energy range where pathlength limitations due to heavy ionization losses are most significant. The sources of these low energy particles must be close. For example, a 1 MeV proton has an integral pathlength $L \lesssim 200$ pc in interstellar gas of $n = 1$ cm^{-3}; and diffusive propagation with a $\lambda \approx 30$ pc restricts the distance of their source to less than ~ 100 pc. A schematic illustration of characteristic magnitudes of parameters relevant to this discussion is given in Figure A4-1. The spatial versus temporal restrictions on protons are schematically shown for an illustrative example of the interstellar medium of hydrogen density

$n_H = 1\ \text{cm}^{-3}$ and cosmic ray diffusion mean free path $\lambda = 30$ pc. A proton, injected at 1 MeV into the medium, lives for $\tau \sim 1.7 \times 10^4$ years before all of its energy has been lost by ionization. Its initial, quasi-straight line propagation (solid line) ultimately is restricted by diffusion (dashed line), as schematically indicated in the figure. Figure A4-1 also shows, for reference, the distances and ages of some astrophysical objects (pulsars, supernovae remnants) which are suspected sources of cosmic rays, and the magnitudes of some galactic parameters relevant to propagation studies. A source at $L \sim 100$ pc with $\lambda \sim 30$ pc would produce an anisotropic flux of $\delta \sim \frac{\lambda}{L} \sim 30\%$. There exist unique relations between age and distance of a source and the energy/charge of particles from this source which can reach the vicinity of the solar system. For example, the Crab is sufficiently far away and young that its possible injection could only be tested at near-relativistic energies, which particles are just now reaching the solar system. The expected anisotropies would be small, less than a few percent. On the other hand, nearer and older sources like VELA could be seen at energies of a few MeV, with much larger anisotropies.

It must be pointed out that source identification, in general, need not be related to the direction of the anisotropy vector. It is highly probable, in fact, that the macrostructure of the interstellar diffusive medium will impose its signature on the propagation vector, which thus will tell us something about the features of the galactic magnetic fields, but not necessarily the source direction. Source identification will be derived from the analysis of a number of observed parameters. Identification of a source is aided by the fact that potential sources are extremely rare within the volumes under discussion; e.g., statistically one expects only a few supernovae remnants in a 10-MeV pathlength source volume, with additional restrictions on source age. Since ionization losses are governed by the square of the particles charge (Z^2), consistency checks between anisotropies and energy spectra of elements differing widely in charge ($1 \lesssim Z \lesssim 26$) can be used to separate local origin elements from those at large distances which may have been decelerated to lower energies in their propagation through the galaxy.

The above illustrations were given for the highly probable, diffusive mode of particle propagation in the galaxy. Should the geometry or general propagation phenomena vary drastically from these assumptions, we nevertheless expect to be able to derive propagation and source information, as discussed in Section A4.1. We have proposed a detector system which, due to its superior directional, charge and energy measurement capabilities can respond to any conceivable situation in the galaxy. We are, on MJU79, still in the initial stages of galactic exploration, but we fully expect to find significant cosmic-ray anisotropies from in situ measurements in the interstellar medium. In fact, the absence of measurable anisotropies would be one of the most surprising results, indicating that either the solar system occupies a most unique position in the galaxy or that a major part of the presently accepted models of galactic processes and parameters require major revision.



DISTANCE (pc)
10^4
10^3
10^2
10^1
10^3
10^4
10^5
10^6
10^7
10^8
LIFETIME (yr)
COSMIC RAY PROTONS
$n_H = 1\ cm^{-3}$
$\lambda_{CR} = 30\ pc$
$\beta = 1$
100 MeV
10 MeV
1 MeV
CRAB
CYGNUS
VELA X
LUPUS
MAXIMUM RANGE FOR DIFFUSIVE PROPAGATION
PSR 1929
PSR 2016
PSR 0950
STRAIGHT PROPAGATION BRANCH
1 MeV PROTON LIFETIME
COSMIC RAY LEAKAGE LIFETIME
DISTANCE TO GALACTIC CENTER
DISTANCE TO EDGE OF SPIRAL ARM
HALF-THICKNESS OF DISK NEAR SUN

Figure A4-1

APPENDIX A5

DEFINITION AND MEASUREMENT OF COSMIC RAY ANISOTROPY

A5.1 DEFINITION OF STREAMING ANISOTROPY

Our energetic particle anisotropy measurements determine the direction and the magnitude of the bulk motion of the observed particle population. In the most general case, the intensity of cosmic ray particles as a function of solid angle Ω at a given position, time, and energy may be represented by:

$$j(\Omega)\ d\Omega = \sum_{\ell,m} j_{\ell m}\ P_{\ell}^{m}(\Omega)\ e^{im\phi}\ d\Omega \qquad (1.1)$$

A complete specification of $j(\Omega)$ would require all $j_{\ell m}$ to be known. A number of natural processes act to smooth out $j(\Omega)$, and for cosmic rays usually only the lower orders in equation (1.1) are required. In fact, the streaming anisotropy of cosmic rays is fully specified by j_{00} and j_{10}, i.e.,

$$\begin{aligned} j(\Omega) &\approx j_{00} + j_{10} \cos\theta \\ &\approx j_{00}\ (1 + \delta \cos\theta) \end{aligned} \qquad (1.2)$$

δ is called the anisotropy, and is related to observation by, e.g.,

$$\delta = \frac{j_{max} - j_{min}}{j_{max} + j_{min}} \qquad (1.3)$$

where j_{max} and j_{min} represent the maximum and minimum fluxes as a function of angle.

Note that if $j(\Omega) = j_{00}$, i.e. isotropic in a co-ordinate frame, an observer in a frame moving at speed $V \ll w$, the random particle speed, will see an anisotropic flux

$$j(\Omega) = j_{00}(1+\delta \cos\theta) \qquad (1.4)$$

where $\delta = \frac{V}{w}\ (2 + \alpha\gamma)$ (1.5)

with $\alpha = \dfrac{T + 2\ m_o c^2}{T + m_o c^2}$

and $\gamma = -\dfrac{\partial\ \ell n\ j_{00}}{\partial\ \ell n\ T}$

if T is the kinetic energy and $m_o c^2$ is the rest energy of the particle. Equations (1.4) and (1.5) describe the Compton-Getting effect.

The anisotropies on an outer solar system mission, i.e., MJU, fall into 3 major categories: interplanetary anisotropies of solar energetic particle fluxes, interplanetary anisotropies of galactic cosmic rays, and interstellar anisotropies of galactic cosmic rays. The latter are a unique and potentially most significant feature of an MJU mission and are discussed further in Appendix A4.

A5.2 MEASUREMENT OF STREAMING ANISOTROPY

An arbitrary streaming anisotropy in the cosmic ray flux is completely defined by 4 independent measurements. For example, consider 4 counter telescopes arranged in an orthogonal VIERBEIN, as shown in Figure A5-1:

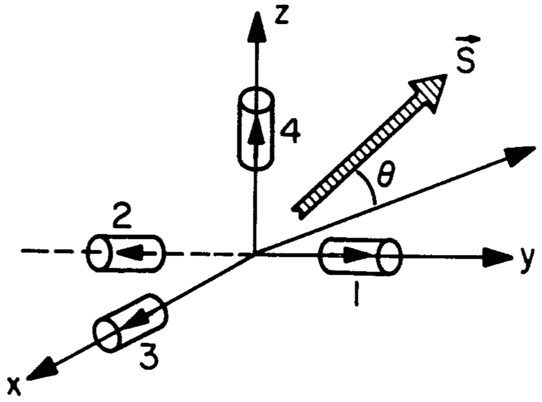


Figure A5-1

For simplicity, let each telescope have the same small solid angle aperture $d\Omega$. The telescopes observe cosmic rays with streaming vector $\vec{S}$. If θ designates the angle between $\vec{S}$ and the viewing direction, then

$$I(\theta) = I_o - S \cos \theta \tag{2.1}$$

and the magnitude of the anisotropy is

$$\delta = \frac{S}{I_o} \tag{2.2}$$

according to Eq. (1.3).

The telescopes 1, 2, 3, and 4 will see the intensities I_i,

$$\begin{aligned} I_1 &= I_o - S_y \\ I_2 &= I_o + S_y \\ I_3 &= I_o - S_x \\ I_4 &= I_o - S_z \end{aligned} \tag{2.3}$$

from which follows

$$\begin{aligned} I_o &= 1/2\ (I_1 + I_2) \\ S_x &= 1/2\ (I_1 + I_2) - I_3 \\ S_y &= 1/2\ (I_2 - I_1) \\ S_z &= 1/2\ (I_1 + I_2) - I_4 \end{aligned} \tag{2.4}$$

Eqs. (2.4) completely specify I_o, the average omnidirectional intensity, and $\vec{S}$, the magnitude and direction of the anisotropy.

The derivation clearly shows that 4 independent directions are an optimal set for determining streaming anisotropies. Less than 4 detectors may miss the largest component of $\vec{S}$ and thus give a totally misleading result.

More telescopes would be needed for higher order anisotropies, but these are generally much smaller and less important in cosmic rays.

APPENDIX A6

MAGNETOSPHERIC TELESCOPE ARRAY

The MTA (Magnetospheric Telescope Array) experiment consists of four charged particle telescopes, each with three detector elements, and three heavily shielded omnidirectional detectors. The electronics utilize discrete components, radiation hardened circuit designs, and pulse strobing techniques to achieve 150 nanosecond time resolution. The design schematics for this experiment are shown in Figures A6-1 and A6-2. The techniques used have been developed and flight proven over the past fifteen years by the University of Iowa. The flights of such U. of Iowa experiments include ones on Relays I and II, OGO A, Injun 4, Mariner 4, IMP's D and E, Mariner 5, OGO D, Injun 5, and Pioneer 11.

A6.1 MAGNETOSPHERIC TELESCOPES

Four single-ended telescopes (referred to as R, S, T and U) are arranged in a symmetric tetrahedral array in order to study angular distributions without need for any mechanically moving devices.

Each telescope (Figure A6-3) consists of three totally depleted silicon surface barrier detectors. The first detector in each array is 10 microns thick with an area of 5 mm^2; the other two elements are 200 microns thick with areas of 10 mm^2. An absorber with thickness of 0.1 grams/cm^2 is placed between detectors two and three. The sides and back of each telescope have an effective minimum shielding of 4.5 grams/cm^2 of inert material. The telescopes have a collimator half angle of 20°, giving a unidirectional geometric factor of 0.02 cm^2-sterad.

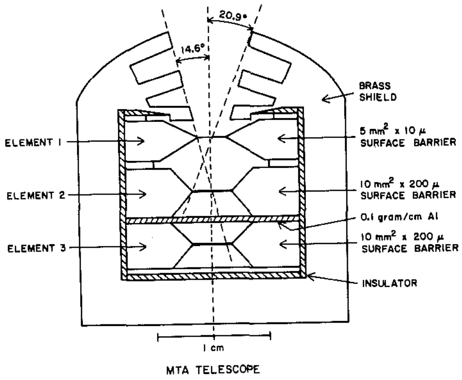


Figure A6-3

The first detector in each stack is used to count protons, alpha particles, and mediums ($Z > 2$). The second detector is used to count protons, alpha particles, mediums ($Z > 2$), and electrons. Single element counting rates and coincidences and anti-coincidences between these detectors allow identification and differential energy measurements of protons, alpha particles, and mediums ($Z > 2$) and eliminate protons and heavier ions with energies less than 43 MeV from the electron measurements.

The third detector, shielded by the first two detectors and 0.1 gram/cm^2 of aluminum, detects high energy protons. Coincidences between the second and third detectors define the directionality and eliminate protons with energies less than 43 MeV from the electron measurements by this detector.

Figure A6-4 shows the electron energy response of each telescope and the electron discrimination levels. It should be noted that levels D_1 and G_1 are set below the minimum energy loss in each detector, thus making each electron measurement integral in energy above its threshold.

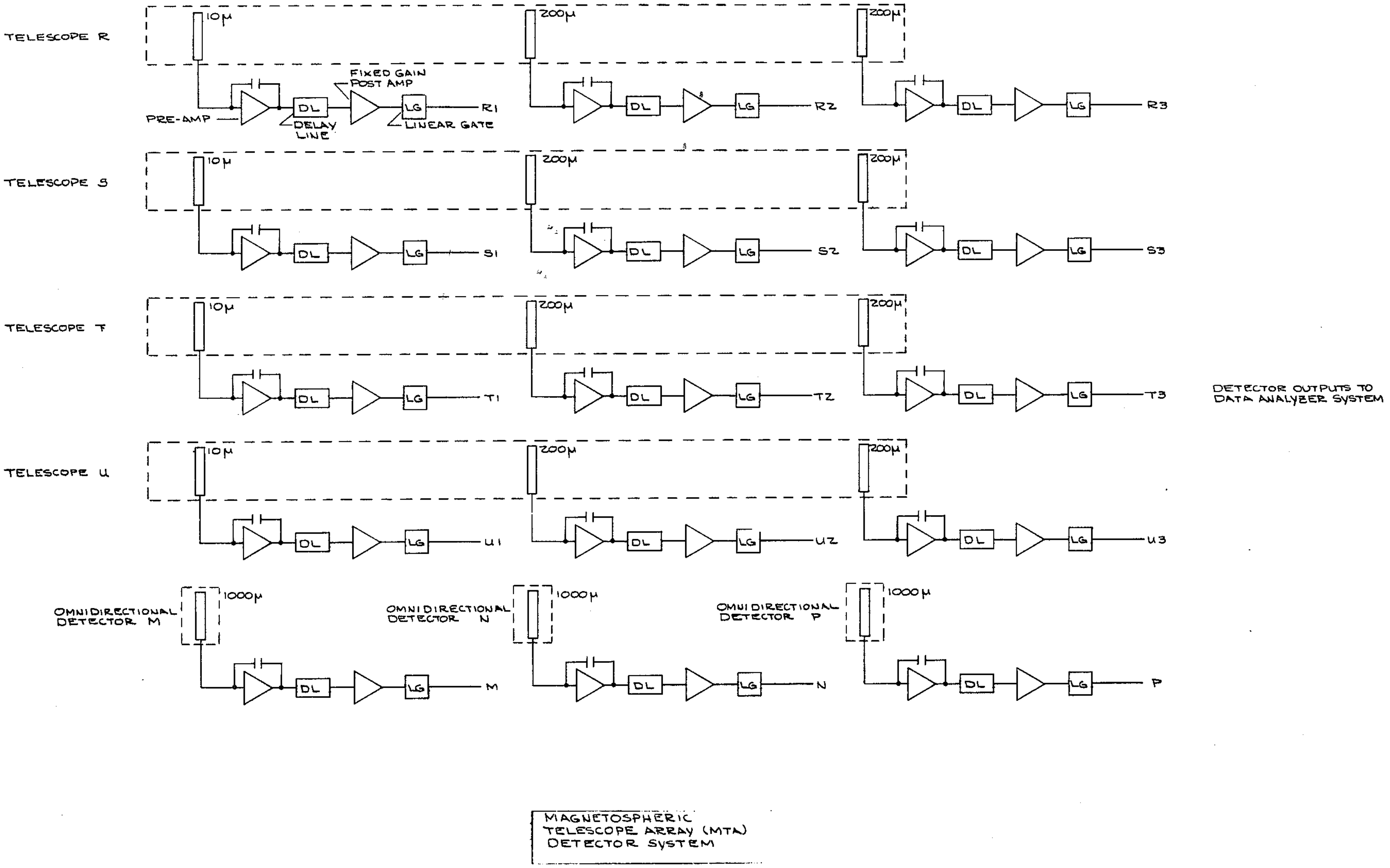

TELESCOPE R
TELESCOPE S
TELESCOPE T
TELESCOPE U
10μ
200μ
200μ
FIXED GAIN POST AMP
PRE-AMP
DL
DELAY LINE
LG
LINEAR GATE
R1
R2
R3
S1
S2
S3
T1
T2
T3
U1
U2
U3
OMNIDIRECTIONAL DETECTOR M
OMNIDIRECTIONAL DETECTOR N
OMNIDIRECTIONAL DETECTOR P
1000μ
M
N
P
DETECTOR OUTPUTS TO DATA ANALYZER SYSTEM
MAGNETOSPHERIC TELESCOPE ARRAY (MTA) DETECTOR SYSTEM

Figure A6-1

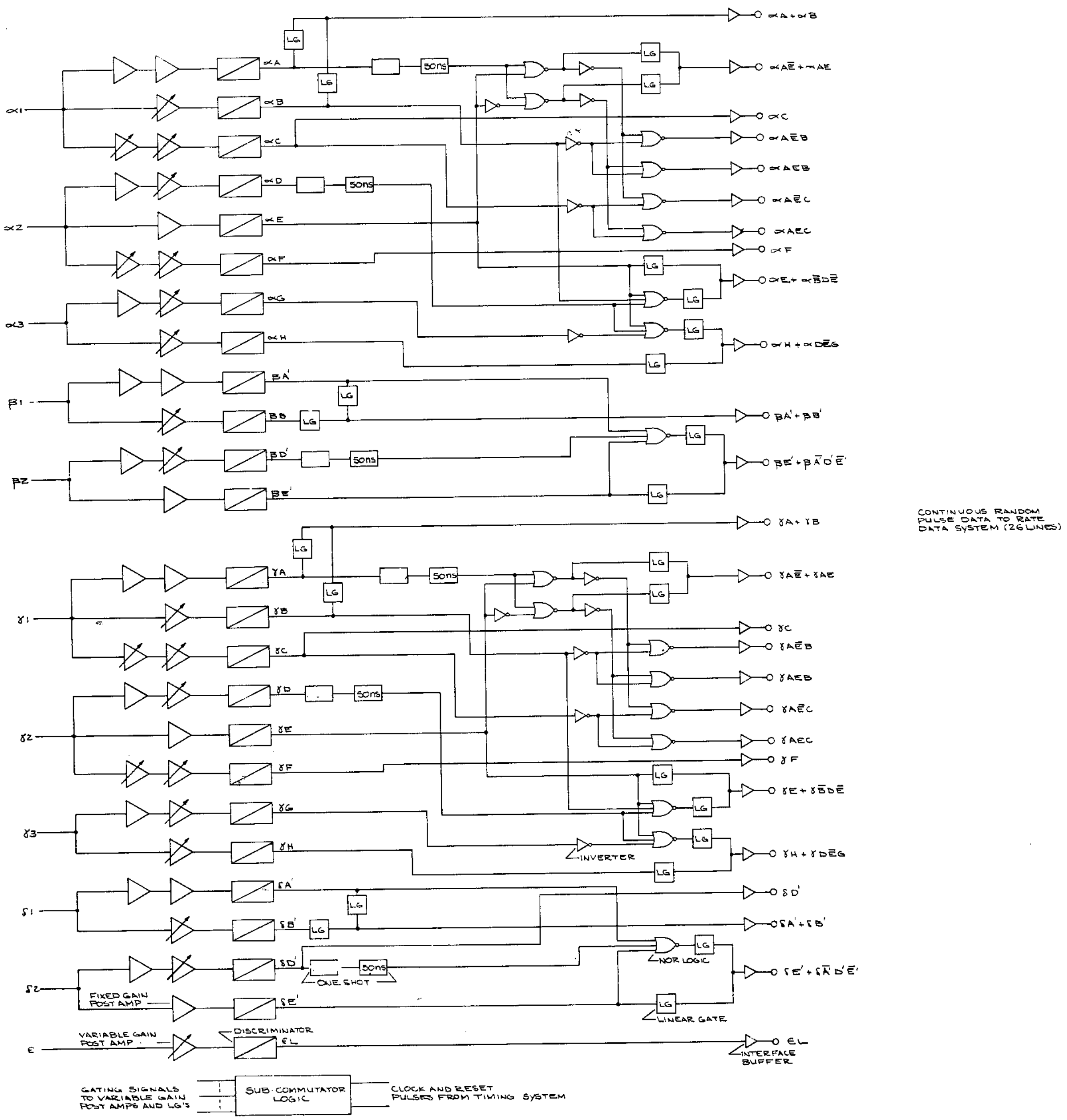

$\alpha 1$
$\alpha 2$
$\alpha 3$
$\beta 1$
$\beta 2$
$\gamma 1$
$\gamma 2$
$\gamma 3$
$\delta 1$
$\delta 2$
ϵ
αA
αB
αC
αD
αE
αF
αG
αH
$\beta A'$
βB
$\beta D'$
$\beta E'$
γA
γB
γC
γD
γE
γF
γG
γH
$\delta A'$
$\delta B'$
$\delta D'$
$\delta E'$
ϵL
LG
50ns
$\alpha A + \alpha B$
$\alpha A\bar{E} + \alpha AE$
αC
$\alpha A\bar{E}B$
αAEB
$\alpha A\bar{E}C$
αAEC
αF
$\alpha E + \alpha \bar{B}D\bar{E}$
$\alpha H + \alpha D\bar{E}G$
$\beta A' + \beta B'$
$\beta E' + \beta \bar{A}'D'\bar{E}'$
$\gamma A + \gamma B$
$\gamma A\bar{E} + \gamma AE$
γC
$\gamma A\bar{E}B$
γAEB
$\gamma A\bar{E}C$
γAEC
γF
$\gamma E + \gamma \bar{B}D\bar{E}$
$\gamma H + \gamma D\bar{E}G$
$\delta D'$
$\delta A' + \delta B'$
$\delta E' + \delta \bar{A}'D'\bar{E}'$
ϵL
CONTINUOUS RANDOM PULSE DATA TO RATE DATA SYSTEM (26 LINES)
INVERTER
NOR LOGIC
ONE SHOT
LINEAR GATE
FIXED GAIN POST AMP
VARIABLE GAIN POST AMP
DISCRIMINATOR
INTERFACE BUFFER
GATING SIGNALS TO VARIABLE GAIN POST AMPS AND LG'S
SUB-COMMUTATOR LOGIC
CLOCK AND RESET PULSES FROM TIMING SYSTEM

Figure A6-2

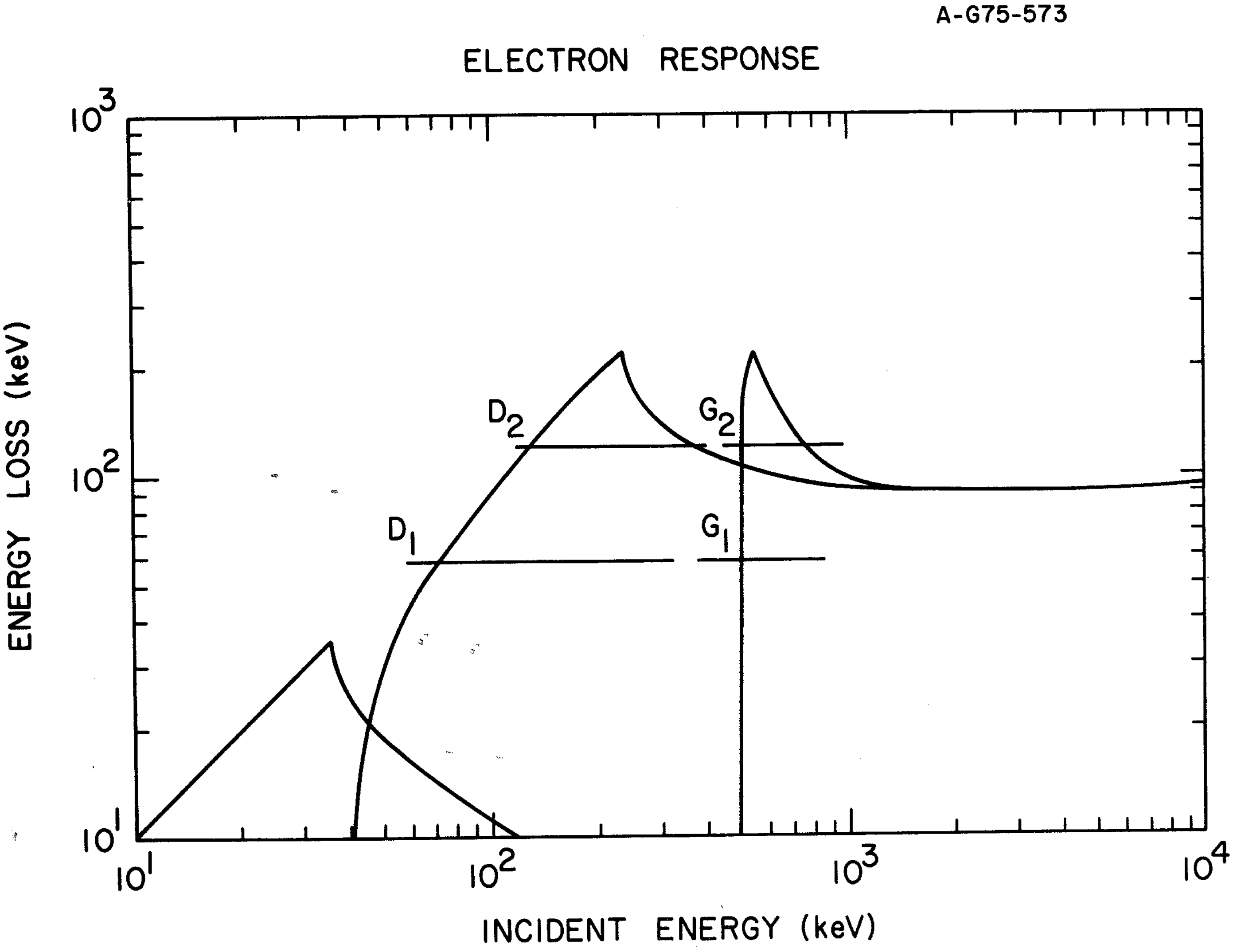

A-G75-573
ELECTRON RESPONSE
ENERGY LOSS (keV)
INCIDENT ENERGY (keV)
10^3
10^2
10^1
10^1
10^2
10^3
10^4
D_2
G_2
D_1
G_1

Figure A6-4

The proton energy response for each telescope is shown in Figure A6-5. The proton energy discrimination levels shown are all well above the maximum electron energy loss in each detector, thus keeping the proton energy measurements free from any electron contamination.

Figure A6-6 shows the alpha particle response of each telescope. The four alpha particle thresholds, C_1, C_2, F_2, and F_3, are high enough above the maximum proton energy loss to provide proton free alpha particle measurements. The C_3, C_4, and F_4 thresholds are used to measure mediums ($Z > 2$).

A6.2 OMNIDIRECTIONAL DETECTORS

Three omnidirectional detectors (referred to as M, N, and P) are included in the instrument package to complement the high energy electron measurements of the telescopes. Each is a one-millimeter-cubical lithium drifted detector. The detectors are spherically shielded by 1.47 g/cm^2 of aluminum, 5.1 g/cm^2 of brass, and 10.9 g/cm^2 of platinum, respectively (Figure A6-7). One energy discrimination threshold will be set at 300 keV, which is less than the minimum energy loss by a charged particle in the 1 mm cube, so that the energy measurement will be integral above the threshold determined by the shielding. A second threshold will be set at 1.5 MeV. This is approximately twice the maximum energy loss for electrons within the detector; hence this level will count only protons or heavier ions.

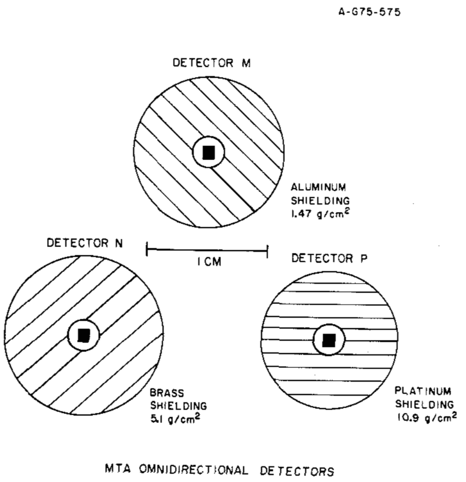


Figure A6-7

A6.3 MTA ELECTRONICS

To make accurate measurements in a high radiation environment such as Jupiter's magnetosphere (and perhaps Uranus') it is necessary to use detectors with small sensitive areas and very fast electronics built with discrete components and radiation hardened circuit designs.

A6.3.1 Basic Electronics

The first element of the system consists of the totally depleted silicon surface barrier detectors. These detectors are over-biased by 25% to make the total volume of the detector sensitive to any energy loss within it and to make the detectors much less susceptible to radiation damage. These detectors are very specialized silicon diodes which are reverse biased, creating a very high electric field within the active volume. This high electric field sweeps out the electron-hole pairs which were created for every 3.6 eV of ionized energy loss within the detector. The charge collection time is less than a nanosecond for the 10 micron detectors and less than 10 nanoseconds for the 200 micron detectors.

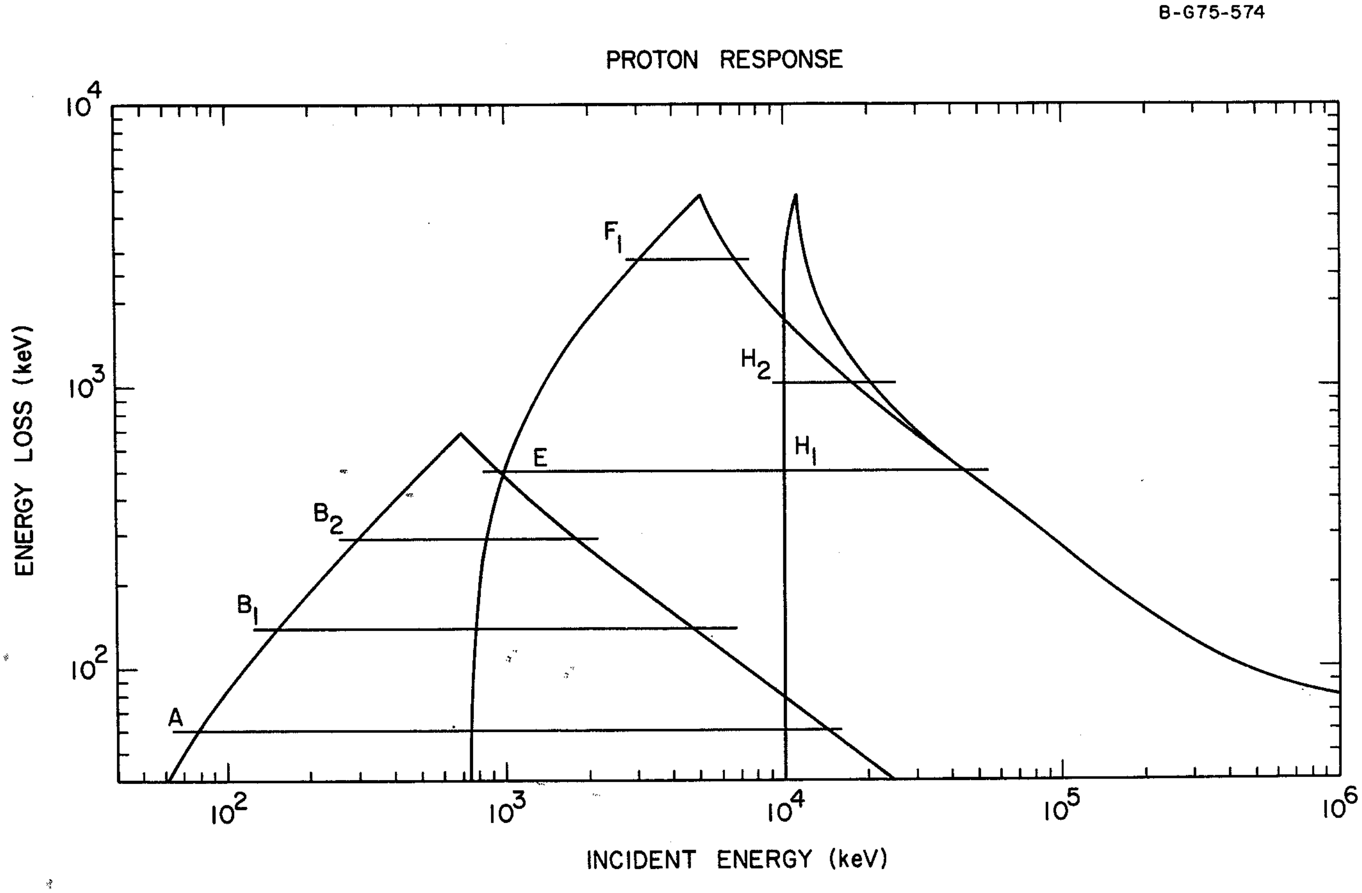

B-G75-574
PROTON RESPONSE
ENERGY LOSS (keV)
INCIDENT ENERGY (keV)
10^4
10^3
10^2
10^2
10^3
10^4
10^5
10^6
F_1
H_2
H_1
E
B_2
B_1
A

Figure A6-5

A-G75-522

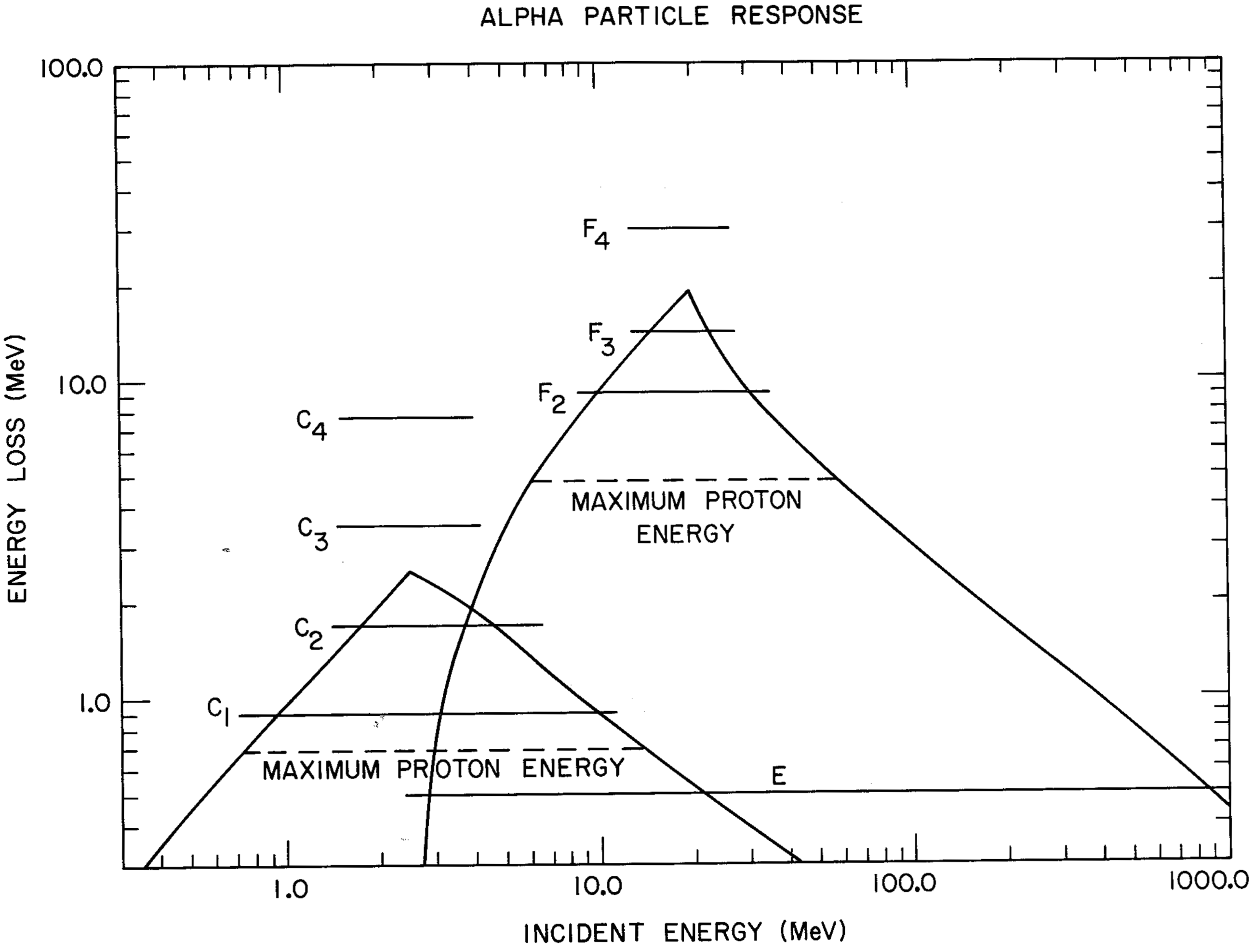


Figure A6-6

The collected charge, which is only 2.67 x 10^{-15} coulombs for 60 keV of energy loss, is amplified by a charge-sensitive amplifier. This device converts the collected charge into a voltage pulse whose height is proportional to the charge and hence to the energy loss. The output from this amplifier has a rise time of less than 20 nanoseconds and a fall time of many microseconds. Since the height of the pulse contains the only relevant information it can be shortened to prevent several pulses from piling up and triggering an energy threshold discrimination incorrectly. For this purpose the output is connected to a shorted delay line which clips the pulse and restores the baseline. The experiment will use 75 nanosecond delay lines which will produce 150 nanosecond wide pulses. These clipped pulses are then amplified by a fixed gain post amplifier whose output is connected to a linear gate as shown in Figure A6-1.

The pulses from the linear gates are amplified once or twice more by either fixed gain post amps or variable gain post amps and then fed into a discriminator. If the amplitude of the pulse is great enough the discriminator will be triggered.

The output of each discriminator is connected to an interface buffer which provides the proper waveform for the data system. The outputs are also used for two types of coincidences as shown in Figure A6-2.

The first type of coincidence uses the leading edge of the output pulse from the lowest energy discriminator connected to the 10 micron detector to trigger a one shot. The pulse from the one shot is 75 nanoseconds wide. The trailing edge of this pulse is used to trigger another one shot with an output pulse width of 50 nanoseconds. The latter pulse is thus delayed in time by 75 nanoseconds from the initiating signal and is used as a strobing pulse to assure the validity of coincidences between the first and second detectors of each telescope. The other discriminators are then connected to the nor logic and strobed at the proper time to see if the logic is proper. The output of the logic is connected to the interface buffer which is in turn connected to the data system.

The second type of coincidence is used for the electron analysis. In this case the lowest level output from the 200 micron detectors is used to generate the strobing pulses. The outputs of the nor logic are again buffered before going to the data system.

A6.3.2 Modes of Analysis

The instrument has four separate analyzers for the telescopes. This scheme allows simultaneous measurements in all four directions. Each telescope is sequentially connected to each analyzer (Figure A6-8). The main reason for doing this is to allow all telescopes in turn to be analyzed with the same electronics, thereby assuring uniformity of results and giving an internal calibration. This method also provides redundancy; in case of failure of any analyzer only time resolution would be lost.

The alpha and gamma analyzers make use of the fast strobing coincidences for both protons and electrons to make a complete spectral analysis. The beta and delta analyzers use the coincidences only for electrons. The

C-G75-586

FRAME	ANALYZER α			ANALYZER β		ANALYZER γ			ANALYZER δ			
	α_1	α_2	α_3	β_1	β_2	γ_1	γ_2	γ_3	δ_1	δ_2	ϵ	
1	R_1	R_2	R_3	S_1	S_2	T_1	T_2	T_3	U_1	U_2	M	
2	R_1	R_2	R_3	S_1	S_3	T_1	T_2	T_3	U_1	U_3	M	
3	R_1	R_2	R_3	S_1	S_2	T_1	T_2	T_3	U_1	U_2	N	
4	R_1	R_2	R_3	S_1	S_3	T_1	T_2	T_3	U_1	U_3	N	
5	U_1	U_2	U_3	R_1	R_2	S_1	S_2	S_3	T_1	T_2	M	
6	U_1	U_2	U_3	R_1	R_3	S_1	S_2	S_3	T_1	T_3	M	
7	U_1	U_2	U_3	R_1	R_2	S_1	S_2	S_3	T_1	T_2	P	
8	U_1	U_2	U_3	R_1	R_3	S_1	S_2	S_3	T_1	T_3	P	
9	T_1	T_2	T_3	U_1	U_2	R_1	R_2	R_3	S_1	S_2	M	
10	T_1	T_2	T_3	U_1	U_3	R_1	R_2	R_3	S_1	S_3	M	
11	T_1	T_2	T_3	U_1	U_2	R_1	R_2	R_3	S_1	S_2	N	
12	T_1	T_2	T_3	U_1	U_3	R_1	R_2	R_3	S_1	S_3	N	
13	S_1	S_2	S_3	T_1	T_2	U_1	U_2	U_3	R_1	R_2	M	
14	S_1	S_2	S_3	T_1	T_3	U_1	U_2	U_3	R_1	R_3	M	
15	S_1	S_2	S_3	T_1	T_2	U_1	U_2	U_3	R_1	R_2	P	
16	S_1	S_2	S_3	T_1	T_3	U_1	U_2	U_3	R_1	R_3	P	

16 FRAMES = 1 CYCLE

MTA DETECTOR SUB-COMM SEQUENCE

Figure A6-8

epsilon analyzer is a single discriminator with low and high gain being switched alternately to separately detect protons and electrons, respectively. The epsilon analyzer is sequentially connected to the three omnidirectional detectors.

A6.4 ENERGY MEASUREMENTS

A6.4.1 Electrons

Each telescope has four electron energy thresholds: two are differential; the other two are integral. The omnidirectional detectors add three more integral measurements. Figure A6-9 graphically displays the electron measurements. Since the higher energy electrons are relativistic, the proper representation of the energies is in terms of $P^2/2M_0$. Table A6-1 (page A6-12) gives the electron energy ranges of measurement and those of contaminating protons. The contribution of the latter will be determined separately (as shown in the next section) and subtracted. The most salient feature of this table in terms of magnetospheric physics is that the measurements of the first adiabatic invariant ($\mu = P^2_\perp/2M_0B$) will be determined over a range of 10^4 at any point. This will provide a wide range of data from which phase space densities can be calculated.

A6.4.2 Protons

Each telescope has seven proton thresholds. With the coincidence channels, one can construct detailed differential proton spectra from 80 keV to 120 MeV. The energy ranges of measurement of protons are shown in Table A6-2 (page A6-13) and Figure A6-9.

A6.4.3 Alpha Particles

Four alpha particle thresholds are set for each telescope. The differential energy coverage in terms of energy per nucleon is from 0.235 to 7.75 MeV per nucleon. Table A6-3 and Figure A6-9 show the ranges of energy measurement of alpha particles.

TABLE A6-3. Alpha Particle Energy Ranges

Range Label	Alpha Particles Energy Range (MeV)	Geometric Factor
$A \bar{E} C_1$	$0.94 \leq E_\alpha \leq 2.84$	0.02 cm² - sr
$A \bar{E} C_2$	$1.75 \leq E_\alpha \leq 2.84$	"
$A E C_1$	$2.84 \leq E_\alpha \leq 10$	"
$A E C_2$	$2.84 \leq E_\alpha \leq 4.6$	"
C_1	$0.94 \leq E_\alpha \leq 10$	"
C_2	$1.75 \leq E_\alpha \leq 4.6$	"
F_2	$10 \leq E_\alpha \leq 31$	"
F_3	$15 \leq E_\alpha \leq 22.5$	"

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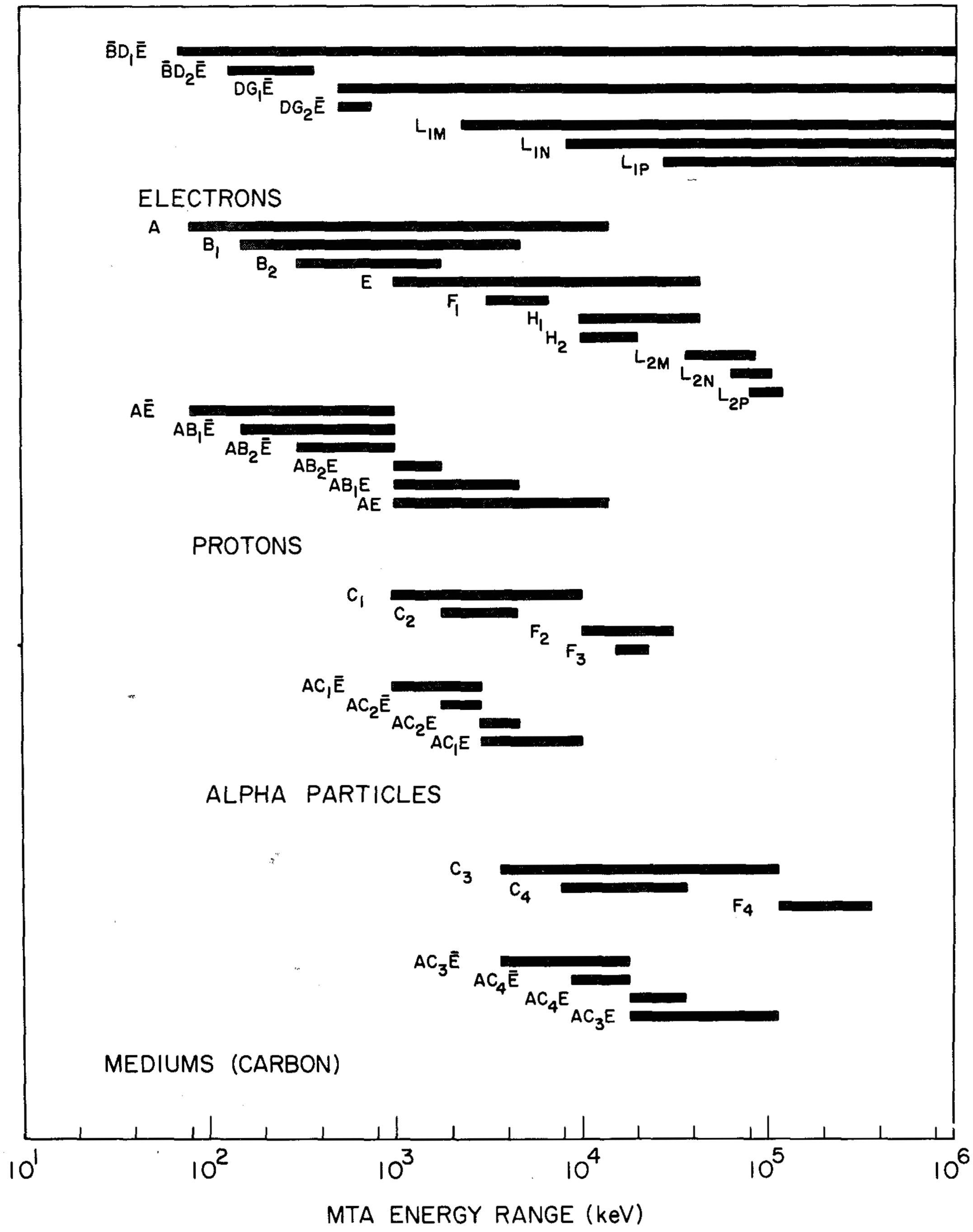


Figure A6-9

TABLE A6-1. Electron Energy Ranges

Range Label	Electrons		Proton Threshold (MeV)	Geometric Factor
	Kinetic Energy (MeV)	$P^2/2M_o$ (MeV)		
$\overline{B}_1 D_1 \overline{E}$	$E_e > .07$	$> 7.5 \times 10^2$	$E_p > 43$	0.02 cm^2 - sr
$\overline{B}_2 D_2 \overline{E}$	$.13 \leq E_e \leq .375$	.15 - .51	$E_p > 43$	0.02 cm^2 - sr
$D_1 G_1 \overline{E}$	$E_e > .5$	$> 7.5 \times 10^{-1}$	$E_p > 43$	0.02 cm^2 - sr
$D_1 G_2 \overline{E}$	$.51 \leq E_e \leq .76$	.75 - 1.3	$E_p > 43$	0.02 cm^2 - sr
L_1 M	$E_e > 2.3$	$> 7.5 \times 10^0$	$E_p > 36$	0.02 cm^2
L_1 N	$E_e > 8.3$	$> 7.6 \times 10^1$	$E_p > 63$	0.02 cm^2
L_1 P	$E_e > 28$	$> 8.0 \times 10^2$	$E_p > 80$	0.02 cm^2

TABLE A6-2. Proton Energy Ranges

Range Label	Proton Energy Range (MeV)	Electron Threshold (MeV)	Geometric Factor
$A \bar{E}$	$0.08 \leq E_p \leq 0.98$	Insensitive to Electrons	0.02 cm^2 - sr
$A E$	$0.98 \leq E_p \leq 14$	"	"
$A \bar{E} B_1$	$0.15 \leq E_p \leq 0.98$	"	"
$A \bar{E} B_2$	$0.3 \leq E_p \leq 0.98$	"	"
$A E B_1$	$0.98 \leq E_p \leq 3.1$	"	"
$A E B_2$	$0.98 \leq E_p \leq 1.77$	"	"
A	$0.08 \leq E_p \leq 14$	"	"
B_1	$0.15 \leq E_p \leq 3.1$	"	"
B_2	$0.30 \leq E_p \leq 1.77$	"	"
E	$0.98 \leq E_p \leq 43$	"	"
F_1	$3.1 \leq E_p \leq 6.6$	"	"
H_1	$9.7 \leq E_p \leq 43$	"	"
H_2	$9.8 \leq E_p \leq 20$	"	"
L_2M	$36 \leq E_p \leq 86$	"	0.02 cm^2
L_2N	$63 \leq E_p \leq 105$	"	"
L_2P	$80 \leq E_p \leq 120$	"	"

All channels are insensitive to protons. Spectral comparison with protons on an energy or energy per nucleon or energy per charge basis will be easily made since such comparisons are well within the energy range coverage of the protons. Thus the proton to alpha particle ratio within the magnetospheres of Jupiter and Uranus can be determined.

A6.4.4 Mediums ($Z > 2$)

It is assumed that the most abundant energetic ions with $Z > 2$ will be carbon, nitrogen, and oxygen but the observed presence of sodium on Io indicates that different abundances might be present in the vicinity of the outer planets. The proposed instrument will give five differential determinations of the energy spectra and can be cross calibrated with the HET and LET to determine abundances in the outer magnetospheres. The differential energy coverage for carbon is shown in Figure A6-9. The geometric factor for all channels is 0.02 cm^2-sr. Nitrogen and oxygen would have somewhat higher energy ranges but in terms of energy per nucleon, they are all similar.

A6.5 ANGULAR DISTRIBUTIONS

1. Angular distributions contain a wealth of information on particle streaming, diffusional processes, satellite sweeping and injection effects, the identification of sources and sinks of particles, and corotational effects. In addition, the axis of rotational symmetry of trapped particle angular distributions gives the direction of the local magnetic vector, without reference to magnetometer data. When magnetometer data are available, the interpretation of angular distributions is greatly enhanced.

2. Thus, the measurement of angular distributions is strongly desirable. There are several techniques for making such measurements on a non-rotating spacecraft:

(a) A two-axis rocking or rotating platform carrying a single directional detector.

(b) A set of several directional detectors of identical characteristics and with different viewing directions, all fixed in spacecraft coordinates.

(c) An active electrostatic and/or electromagnetic beam-sweeping device in conjunction with one or more detectors.

(d) A hybrid combination of the foregoing.

We have rejected technique (a) because of its complexity and the risk associated with mechanically moving equipment on spacecraft; also we have rejected technique (c) because of weight and power constraints and the very great difficulty of covering the desired energy range.

We have adopted technique (b). An ideal system of this type would subdivide the entire unit sphere into n equal solid angles with n of the order of 20 or greater. We have settled on a lesser number, namely n = 4, on the basis of a miscellany of practical considerations--reasonable adequacy for the problem at hand; minimum practical solid angle for low mass telescopes, having relatively thin side shielding; desired time resolution (time required to go through a complete cycle of outputs with a practical telemetry rate); establishment of physical intercalibrations; mass; power; cost; available fields of view on the spacecraft; etc.

In order to determine angular distributions with a fixed array of several telescopes, special care must be taken in construction, choice of detector elements, setting of discrimination levels, etc. to assure that all telescopes have essentially identical characteristics. The final intercomparison will be made with particle beams in the laboratory. The inflight data scheme interchanges amplifier and output electronics among the four telescopes on a cyclic basis, as a further measure toward accurate intercomparison.

3. The adopted criteria for look-directions are as follows:

(a) The look directions should be widely distributed over the unit sphere in order to yield good angular coverage.

(b) The arrangement of look directions should be a non-degenerate one. For studying a quasi-stationary trapped particle population, for example, no two telescopes should look in diametrically opposite directions.

(c) Further in the interest of preventing degeneracy, the orientation of the array of telescopes on the spacecraft should be such as to avoid predictable situations at both Jupiter and Uranus in which two or more look directions are at nearly the same angle to $\pm \hat{B}$, where $\hat{B}$ is the local magnetic field unit vector.

(d) No telescope axis should be within 40° of pointing toward the sun, because of the sensitivity of the first element of the telescope to solar electromagnetic radiations.

(e) All detectors should have fields of view unobstructed by physical obstacles (S/C structure, booms, etc.) to avoid occultation of their solid angles as well as sun "glints".

Criteria (a) and (b) are met with a symmetrical tetrahedral arrangement of four telescopes, the angle between the axes of any pair of telescopes being arc cos (- 1/3) = 109.5°. From examination of the proposed spacecraft structure and the in-flight orientation program for the spacecraft, it appears that criteria (c), (d), and (e) can also be met. Criterion (d) will be violated early in flight and perhaps during subsequent orientation maneuvers when the transmitting antenna is not pointed at the earth; during such periods the experiment must be turned off. Criterion (c) can be met during most of the Jovian encounter on the basis of existing knowledge. But, because of ignorance of the magnetic topology at Uranus, any specific arrangement of telescopes may be in a degenerate situation at times; however, general consideration of the problem indicates that, even at Uranus, a degenerate situation will be of only limited duration for the arrangement that we have adopted. The proposed location of the MTA is near the outboard end of the instrumentation boom at the same position as the CRS cosmic ray instrument on the MJS spacecraft.

Each telescope has a conical field of view with half angle about 20°.

4. It is evident that data from four telescopes looking in four non-degenerate directions can determine four independent parameters in an angular distribution of known or assumed form. Two of these parameters can be the direction cosines of the axis of symmetry of the distribution.

Examples:

(a) Corotational streaming of an angular distribution that is isotropic in the corotating frame of reference:

$$j = M [1 + K \cos \beta] .$$

Four parameters: M, K, and two direction cosines of the streaming direction.

(b) "Pancake" distribution of trapped particles

$$j = M | \sin^n \beta | .$$

Four parameters: M, n, and two direction cosines of the axis of symmetry.

(c) Sum of isotropic and "pancake" distributions

$$j = M [1 + K \sin^2 \beta] .$$

Four parameters: M, K, and two direction cosines of the axis of symmetry.

(d) More general case of (c)

$$j = M [1 + K |\sin^n \beta |] .$$

Five parameters: Can determine M, two direction cosines of the axis of symmetry and K(n) or n(K). If B is available from magnetometer data, can determine M, K, and $\hat{n}$ and can check one direction cosine of $\hat{B}$.

(e) Sum of "pancake" and "dumbbell" distributions

$$j = M [\cos^m \beta + K |\sin^n \beta |] .$$

Six parameters: If $\hat{B}$ known, can determine remaining four parameters: M, m, K, and n.

The foregoing descriptive analysis is straightforwardly obvious only for telescopes of infinitesimal solid angle. For actual telescopes of finite solid angle, integration of the assumed angular distribution over the angular response function of the telescope must be performed. This is a numerical complication but not one of principle.

5. As a first example, an explicit solution is given for case (a) of paragraph 4. for our tetrahedral array of telescopes, assuming infinitesimal solid angles. Let the unidirectional intensity be assumed to be

$$j = M\left[\, 1 + K \cos\beta \,\right]$$

with the angle β measured from an unknown vector streaming direction. The intensities measured by the four telescopes are denoted by j_1, j_2, j_3, and j_4. A right handed orthogonal coordinate system, fixed in spacecraft coordinates, is arranged so that the spherical polar coordinates of the axes of the four telescopes are:

$$\theta_1 = 54^\circ.7 \qquad \varphi_1 = 0^\circ$$

$$\theta_2 = 54^\circ.7 \qquad \varphi_2 = 180^\circ$$

$$\theta_3 = 125^\circ.3 \qquad \varphi_3 = 90^\circ$$

$$\theta_4 = 125^\circ.3 \qquad \varphi_4 = 270^\circ$$

The (unknown) spherical polar coordinates of the vector streaming direction are denoted by Γ and χ. The problem is to find M, K, Γ, and χ in terms of the observed intensities j_1, j_2, j_3, and j_4.

By the law of cosines

$$\cos\beta_i = \cos\theta_i \cos\Gamma + \sin\theta_1 \sin\Gamma \cos(\chi - \varphi_i), \qquad i = 1, 2, 3, 4.$$

Thus,

$$\cos\beta_1 = \frac{1}{\sqrt{3}} (\cos\Gamma + \sqrt{2} \sin\Gamma \cos\chi)$$

$$\cos\beta_2 = \frac{1}{\sqrt{3}} (\cos\Gamma - \sqrt{2} \sin\Gamma \cos\chi)$$

$$\cos\beta_3 = -\frac{1}{\sqrt{3}} (\cos\Gamma - \sqrt{2} \sin\Gamma \sin\chi)$$

$$\cos\beta_4 = -\frac{1}{\sqrt{3}} (\cos\Gamma + \sqrt{2} \sin\Gamma \sin\chi).$$

The four unknown quantities are given explicitly by the following:

$$M = (j_1 + j_2 + j_3 + j_4)\ /4, \text{ independent of all other parameters}$$

$$\tan \chi = \left(\frac{j_3 - j_4}{j_1 - j_2} \right)$$

$$\tan \Gamma = \frac{\sqrt{2}}{\cos \chi} \quad \frac{j_1 - j_2}{(j_1 + j_2) - (j_3 + j_4)}$$

$$K = \frac{\sqrt{3}}{4M \cos \Gamma} \left[(j_1 + j_2) - (j_3 + j_4) \right].$$

The omnidirectional intensity

$$J = \int_{4\pi} j d\Omega = 4\pi M = \pi (j_1 + j_2 + j_3 + j_4).$$

6. As a second example, an explicit solution is given for case (c) of paragraph 4.

$$j = M \left[1 + K \sin^2 \beta \right]$$

with the angle β measured from an unknown vector axis of symmetry $(\hat{B})$. By the same procedure as in paragraph 5, we find

$$\tan \chi = - \left(\frac{j_3 - j_4}{j_1 - j_2} \right)$$

$$\tan \Gamma = \frac{(j_1 + j_2) - (j_3 + j_4)}{(j_1 - j_2) + (j_3 - j_4)} \quad \frac{\sqrt{2}}{(\cos \chi + \sin \chi)}$$

$$M = \frac{(j_1 + j_2 + j_3 + j_4)}{4\ (1 + 2K/3)}$$

or

$$M = \frac{(j_1 + j_2 + j_3 + j_4}{4} + \frac{1}{2\sqrt{2}} \quad \frac{(j_1 - j_2)}{\cos \Gamma \sin \Gamma \cos \chi}$$

$$K = - \frac{3}{4\sqrt{2M}} \quad \frac{(j_1 - j_2)}{\cos \Gamma \sin \Gamma \cos \chi} .$$

The omnidirectional intensity,

$$J = \int_{4\pi} j d\Omega = 4\pi M(1 + 2K/3)$$

$$J = \pi (j_1 + j_2 + j_3 + j_4).$$

7. For the actual telescopes having finite solid angles, final solutions will be obtained by iteration using the solutions for infinitesimal solid angles as the starting point and performing integrations over the angular response functions of the telescopes.

8. The tentatively adopted spherical polar coordinates of the axes of the four telescopes are given in the following table in conventional spacecraft coordinates. The specified angles refer to unit vectors along the respective axes of the telescopes with the unit vectors pointing in the directions from which particles enter the collimators. The polar angle θ is measured from the +Z (anti-earth-pointing) axis, and the azimuthal angle φ is measured in the XY plane from the +X axis to the projection of the unit vector on that plane.

Telescope	θ	φ
R	25°.00	0°.00
S	120 .09	70 .67
T	84 .47	180 .00
U	120 .09	289 .33

This orientation of the tetrahedral array meets criteria (d) and (e) of paragraph 3 and appears to offer a reasonably satisfactory approach to meeting criterion (c) also.

A6.6 SPURIOUS EFFECTS

Any system of charged particle detectors that is practical for the MJU mission in terms of mass and power is subject to a variety of physical and electronic effects which cause departures from the idealized performance often assumed in simplified analyses. Such effects, though usually called spurious, are nonetheless predictable and calculable under specific assumptions. Included among spurious effects are (a) pulse pile-up; (b) penetration of detector elements by particles energetic enough to pass through the side and back shielding of telescopes; and (c) accidental coincidences and anti-coincidences.

Effects (a) and (c) are strongly dependent on the intensities as well as on the form of the spectra of the various species of particles under consideration. These effects have been minimized by the use of small detectors and fast electronics. Effect (b) is independent of intensity but is dependent on the form of relevant spectra. These various problems have been analyzed for the MTA and are summarized briefly as follows:

(a) Pulse Pile-Up

For any position in the Jovian magnetosphere in to the intended radius of closest approach of 5.8 R_J in the magnetic equatorial plane, pulse pile-up is a trivial problem for both telescope elements and cubical detectors.

(b) Back Penetrations of the Telescopes

The minimum shielding of the back of the telescope is 4.8 grams/cm^2. Electrons $E_e > 7$ MeV and protons $E_p > 71$ MeV can pass through the telescope in the opposite-to-nominal direction. There are no contributions by back-penetrating particles of lesser energies. Those of higher energies are properly measured by the spherical detectors.

(c) Accidental Coincidences and Anti-Coincidences

The suppression of anti-coincidences by accidentals is found by detailed analysis to be a minor problem even to maximum Jovian encounter conditions.

However, several coincidence channels will require substantial correction under maximum Jovian encounter conditions. Such corrections can be made with reasonable certainty by using the full body of data, especially the single element rates.

(d) Side-Wall Penetrations of the Telescopes

There is no problem with side-wall penetrating protons under any anticipated conditions. The problem with electrons is strongly dependent on their spectral form. For the 200μ detectors and for differential power law spectrum of the form $E^{-\gamma}$, the collimated to uncollimated counting rate ratio caused by $E_e > 7$ MeV electrons (the minimum energy required to penetrate the side wall) is 10/1 for $\gamma = 2.4$. For $\gamma = 1.9$, the ratio is 1/1. Hence, there will be conditions in the inner magnetosphere of Jupiter during which the high energy electron channels of the telescope will be ambiguous (i.e., the proper geometric factor will be uncertain by a factor of about 4). Even in such a case, the responses of the spherically shielded detectors will give unambiguous coverage of the high energy portion of the electron spectrum, though angular distribution information will be lost.

It is noteworthy that the three spherical detectors are almost completely immune to spurious effects. Also, the intensity situation at Uranus will almost certainly cause no significant problems for either telescopes or spherical detectors.

Counting rates caused by gamma rays and neutrons from the radioisotope thermoelectric generators (RTG's) are of trivial importance during magnetospheric traversals.

APPENDIX A7

ELET

A schematic diagram of an ELET telescope is shown in Figure A7-1. It is a single-ended telescope with a geometrical factor of 0.06 cm^2 ster. This telescope has been designed to extend multi-dimensional analysis to the lowest practical energies. This energy range of analysis for different charges is shown in Figure A7-2 for both two-parameter and three-parameter analysis.

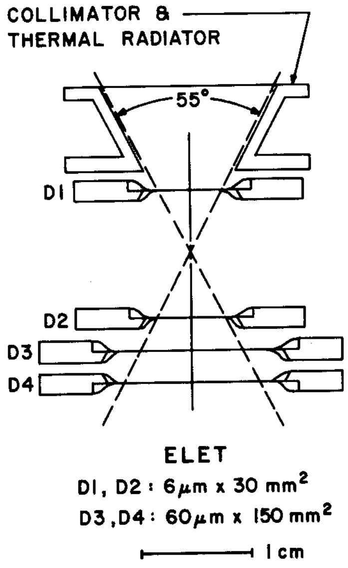


FIGURE A7-1: Schematic of ELET

A block diagram and truth table for the electronics system is shown in Fig. A7-3. This system is built of the same circuitry modules developed for the HETS and LETS for the MJS '77 mission. In operation the electronics system is very similar to the LET system described in the following Appendix, A8, although various linear gains and thresholds are different (see Table 7-1 of the main proposal). The sum $\Sigma D_1+K_1D_2+K_2D_3=SD$ is applied to a threshold to separate hydrogen and helium events (Type 1) from all heavier events (Type 2). The Type 1 and Type 2 events are separately stored and read out into telemetry with equal priority in the readout polling scheme. The pulse-height analyzers used have 4096 channels.

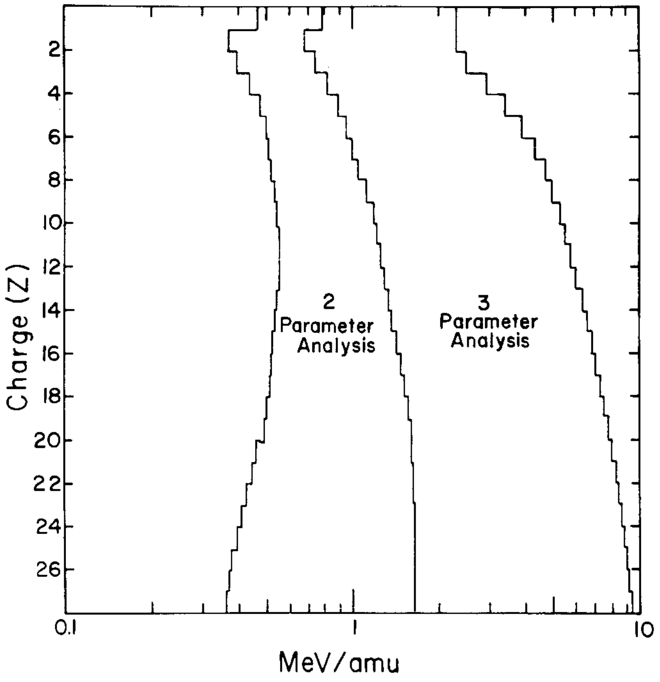
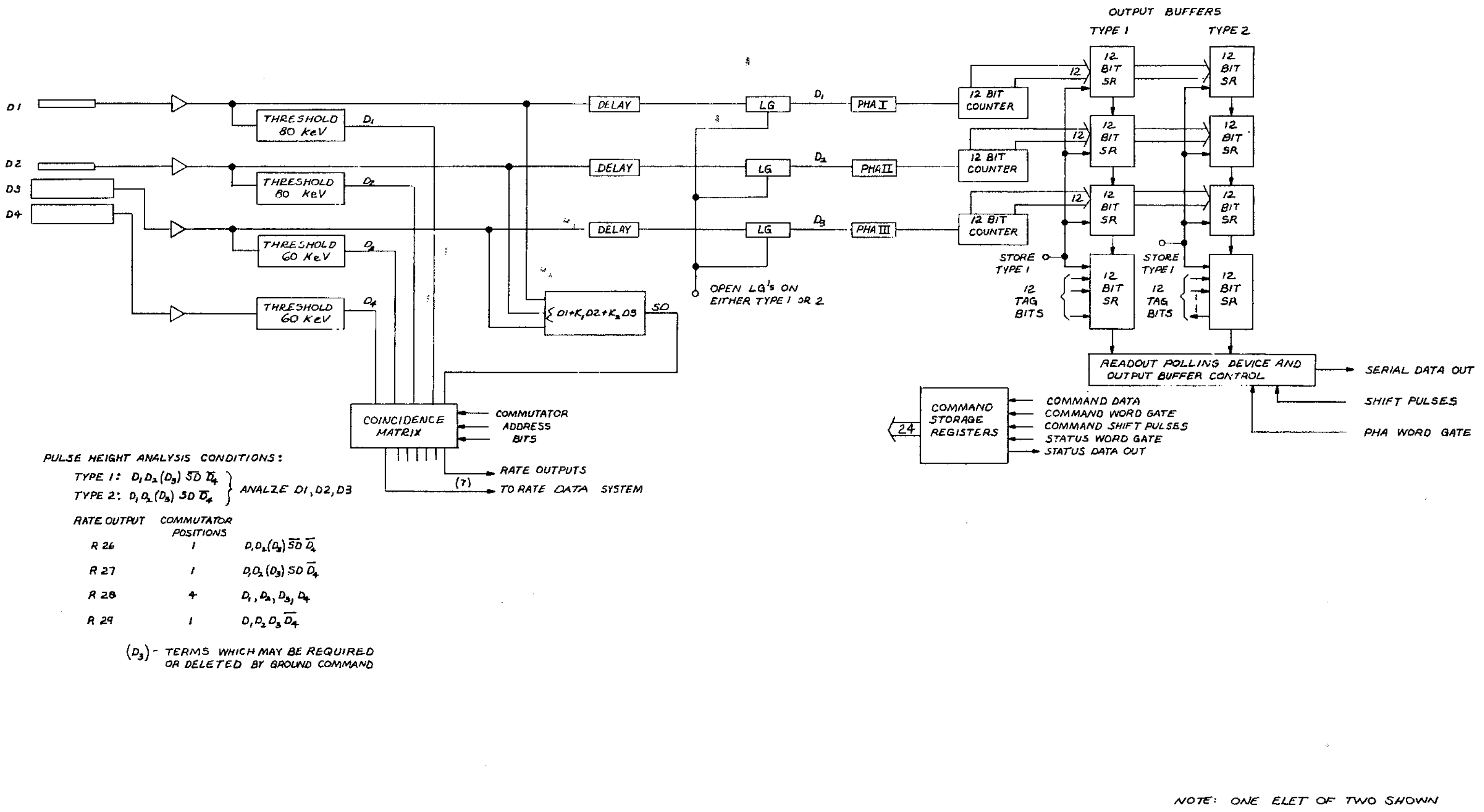


FIGURE A7-2

The thicknesses of the dE/dx and E detectors (6 and 60μ, respectively) are matched so that the energy losses in the dE/dx detectors will always be safely above the noise for these detectors, even for protons. The system noise for the D_1 and D_2 signals will be 25-30 keV FWHM, allowing clean thresholds to be set at 80 keV. These thresholds are then 5σ below the average signals generated in D_1 and D_2 by a proton not quite reaching D4. Figure A7-4 (see Page A7-3) shows the energy loss to be expected in each element for the different isotopes of H and He. Counters thinner than 6μ are available, but in addition to the problems of signal versus noise for protons as noted above, such thin counters are basically



PULSE HEIGHT ANALYSIS CONDITIONS:

TYPE 1: $D_1 D_2 (D_3) \overline{SD}\, \overline{D_4}$ } ANALZE D1, D2, D3
TYPE 2: $D_1 D_2 (D_3)\, SD\, \overline{D_4}$ }

RATE OUTPUT	COMMUTATOR POSITIONS	
R 26	1	$D_1 D_2 (D_3) \overline{SD}\, \overline{D_4}$
R 27	1	$D_1 D_2 (D_3)\, SD\, \overline{D_4}$
R 28	4	D_1, D_2, D_3, D_4
R 29	1	$D_1 D_2 D_3 \overline{D_4}$

(D_3) - TERMS WHICH MAY BE REQUIRED OR DELETED BY GROUND COMMAND

NOTE: ONE ELET OF TWO SHOWN

ELET ELECTRONICS
MJU

FIGURE A7-3

unsuited for charge studies because of thickness variations which are ~ 1μ. With our maximum opening angle of 27.5°, the maximum pathlength is 1.13 times that for a vertical trajectory. This pathlength variation is compatible with the expected 1/6 or 16% variation to be expected in the dE/dx detector thickness. These variations will limit individual charge separation up to Z ∿ 10. For heavier nuclei the resolution is ∿2 charge units.

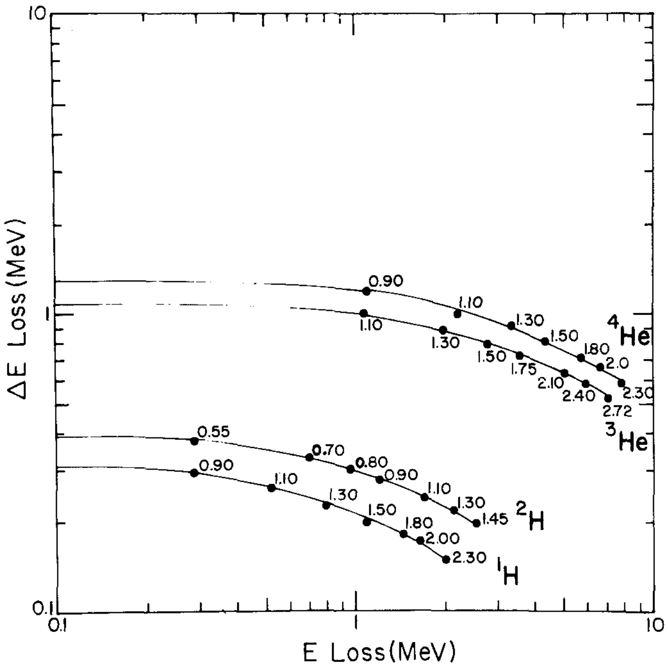


FIGURE A7-4: ΔE vs. E

Multi-dimensional coincidence/pulse-height analysis techniques are essentially background free, whereas a single parameter analysis tends to have a large residual "background" of events that is frequently very difficult to evaluate. As a result of this low background and larger geometry factor, we expect the ELET to be ∿50 times more sensitive than the LET-II telescope on Pioneers 10 and 11. The ELET telescope will thus be able to measure accurately the quiet-time intensity of all types of particles which would be obscured in the background of a single parameter analysis. The geometry factor is large enough so that at quiet-time levels useful flux measurements can be made for most all nuclei over an extended period of time. For example, in ∿1 year we expect ∿200 oxygen nuclei at ∿1 MeV, even if the spectrum does not turn up.

APPENDIX A8

LOW ENERGY TELESCOPE

The low energy telescope (LET), schematically illustrated in Figure A8-1, is intended to measure the energy spectrum and anisotropy of cosmic-ray nuclei. This measurement is performed over the charge range from 1 to 28.

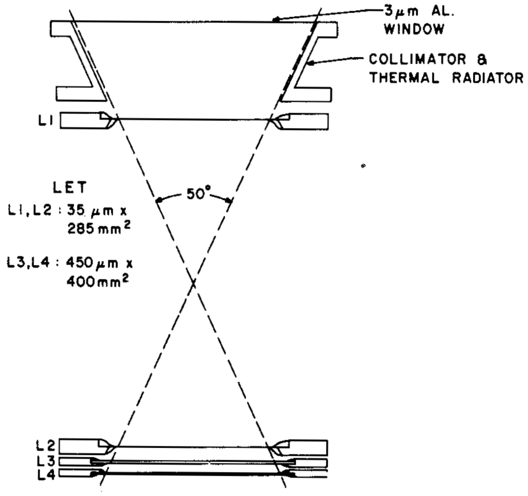


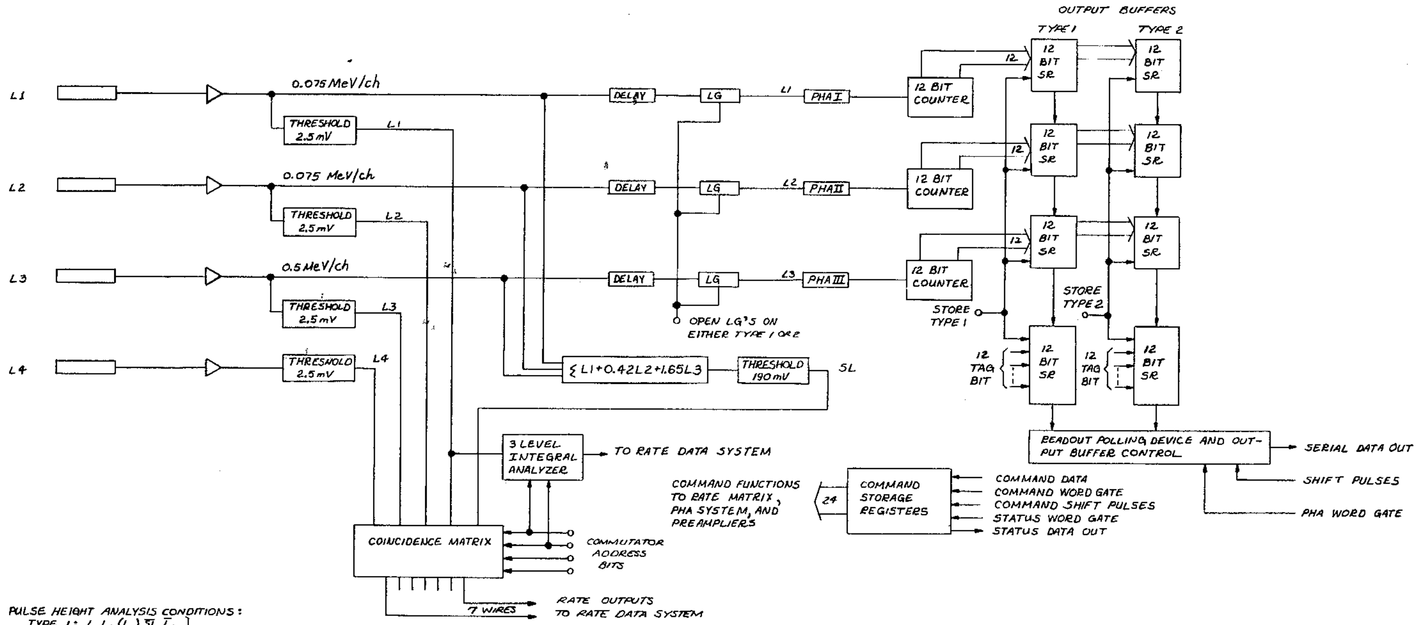
FIGURE A8-1

Anisotropies are measured by comparing results from the four LET's on the spacecraft. An important feature is the use of keyhole detectors for L1 and L2. The active area of the detectors is accurately defined by using a mask to precisely determine the area over which the Au and Aℓ contacts are deposited. The keyhole design allows precise measurement of the geometry factor of each LET.

Beyond the charge-sensitive preamplifiers and shaping amplifiers, a LET electronics system consists of coincidence circuitry to determine if an event has occurred, pulse-height analyzers and a rate accumulator system as shown in Figure A8-2. As summarized in Table A8-1 and shown in Figure A8-2, there are two analysis modes based upon the amplitude of the sum Σ L1 + 0.42 L2 + 1.65 L3, and events are labeled Type 1 or Type 2 accordingly. These events are separately stored and normally read out into telemetry with equal priority in the readout polling scheme. Detector thresholds are set at 200 KeV for L1 and L2 and at 1 MeV for L3 and L4, and additionally there is a four-level integral analyzer on L1 (see Table A8-2). Pulse-height analyzers with 4096-channels are provided for L1, L2 and L3. A versatile command system allows for change of the pulse-height analysis conditions, the rate logic, readout priority and power on/off control of the various preamplifiers.

With the specified detector thresholds, the energy ranges specified in Table A8-1 are calculated. These calculations are based on the standard energy-loss tables; previous experience shows that substantial corrections to the tables will have to be made on the basis of calibration data.

Figures A8-3 and A8-4 show the response to particles of several types. The energy loss, ΔE, in L1 (Figure A8-3) or L1 + L2 (Figure A8-4) is plotted as a function of residual energy, E', in L2 (Figure A8-3) or L3 (Figure A8-4). As illustrated by the different particle tracks in Figures A8-3 and A8-4, the ΔE and E' for each analyzed particle can be used to calculate the mass of the particle. Any uncertainties in ΔE or E' result in uncertainties in the calculated mass. One of the largest uncertainties is the angle of incidence of the particle. As an example, the calculated locus of ^{16}O events is shown for the two extreme angles of incidence, 0^0 and 25^0.



PULSE HEIGHT ANALYSIS CONDITIONS:

TYPE 1: $L_1 L_2 (L_3) \overline{5L}\, \overline{L_4}$ } ANALYZE L1, L2, L3
TYPE 2: $L_1 L_2 (L_3)\, 5L\, \overline{L_4}$

RATE OUTPUTS	COMMUTATOR POSITION	
R10	1	$L_1 L_2 (L_3) \overline{5L}\, \overline{L_4}$
R11	1	$L_1 L_2 (L_3)\, 5L\, \overline{L_4}$
R12	4	L_1, L_2, L_3, L_4
R13	1	$L_1 L_2 L_3 \overline{L_4}$

(L3) - TERMS WHICH MAY BE REQUIRED OR DELETED BY GROUND COMMAND

NOTE: ONE LET OF FOUR SHOWN

LET ELECTRONICS
MJU

Figure A8-2

TABLE A8-1: LET ENERGY RANGE

(Energies in MeV/nuc)

MODE OF ANALYSIS	PARTICLE TYPE			
	^{1}H	^{4}He	^{16}O	^{56}Fe
L1	0.5-1.7	0.4-1.6	0.3-3.3	0.2-3.8
L1L2	1.7-3.0	1.6-2.7	3.3-5.3	3.8-6.3
L1L2L3	3.0-8.4	2.7-8.4	5.3-18	6.3-35

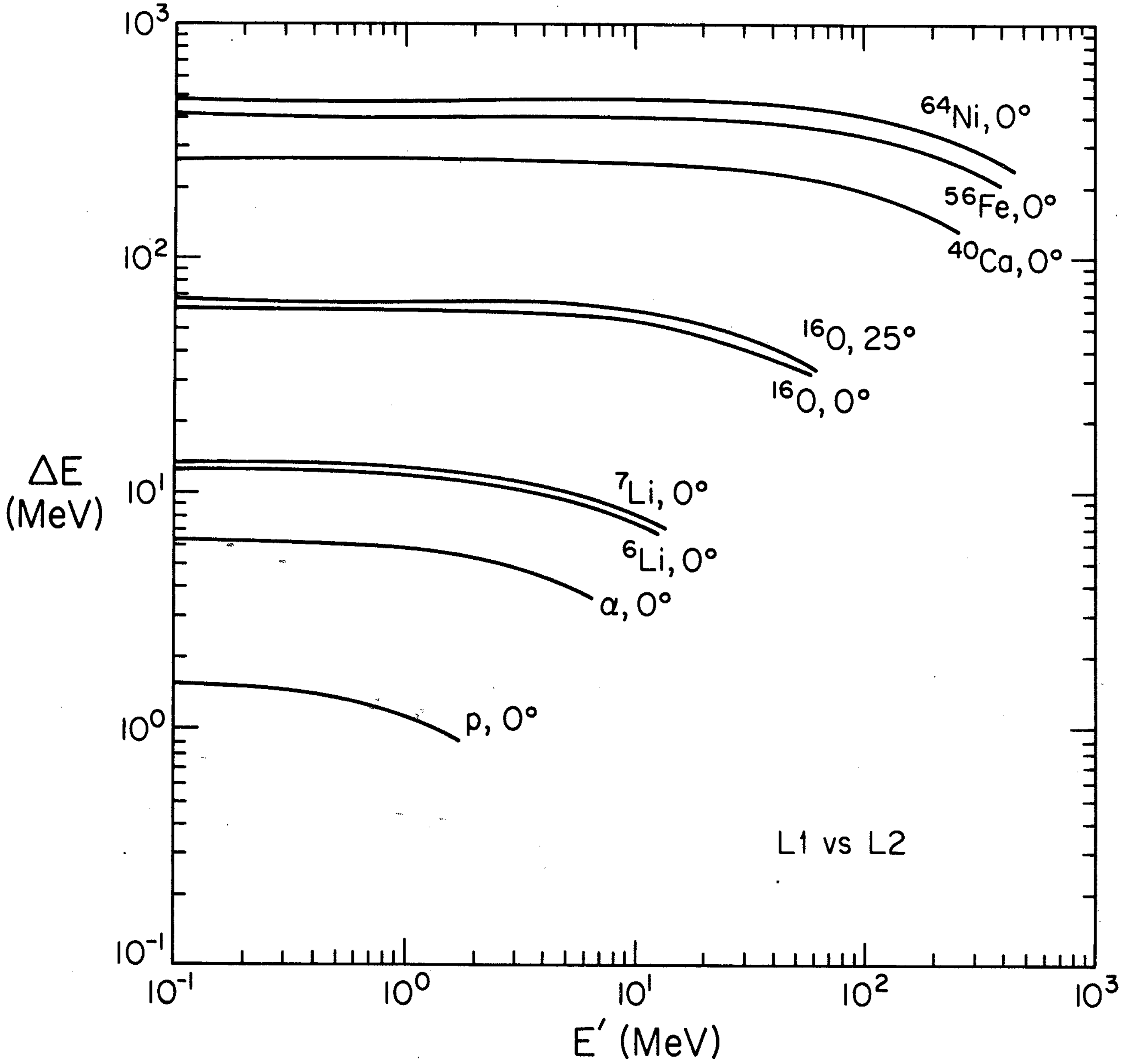
(Table includes effects of window and discriminator thresholds.)

TABLE A8-2: LET ANALYSIS MODES AND RATES

Analysis Mode[1)]	Typical Event Type	
L1•L2•(L3)•SL•L4	^{1}H and ^{4}He: $1.7 \lesssim E \lesssim 8.4$ MeV/nuc	
L1•L2•(L3)•SL•L4	$Z \geq 3$: $3.5 \lesssim E \lesssim 18$ MeV/nuc	
Rate Information[2)]	**Typical Event Rate**	
L1•L2•(L3)•SL•L4	Rate of ^{1}H, ^{4}He: $1.7 \lesssim E \lesssim 8.4$ MeV/nuc	
L1•L2•(L3)•SL•L4	Rate of $Z \geq 3$: $3.5 \lesssim E \lesssim 18$ MeV/nuc	
L1•L2•L3•L4	Rate of ^{1}H, ^{4}He: $3 \lesssim E \lesssim 8.4$ MeV/nuc	
L11	L1 > 0.45 MeV	Integral Analyzer on LI
L12	L1 > 1.88 MeV	
L13	L1 > 7.5 MeV	
L14	L1 > 75.7 MeV	
L1		Single Detector Rates
L2		
L3		
L4		

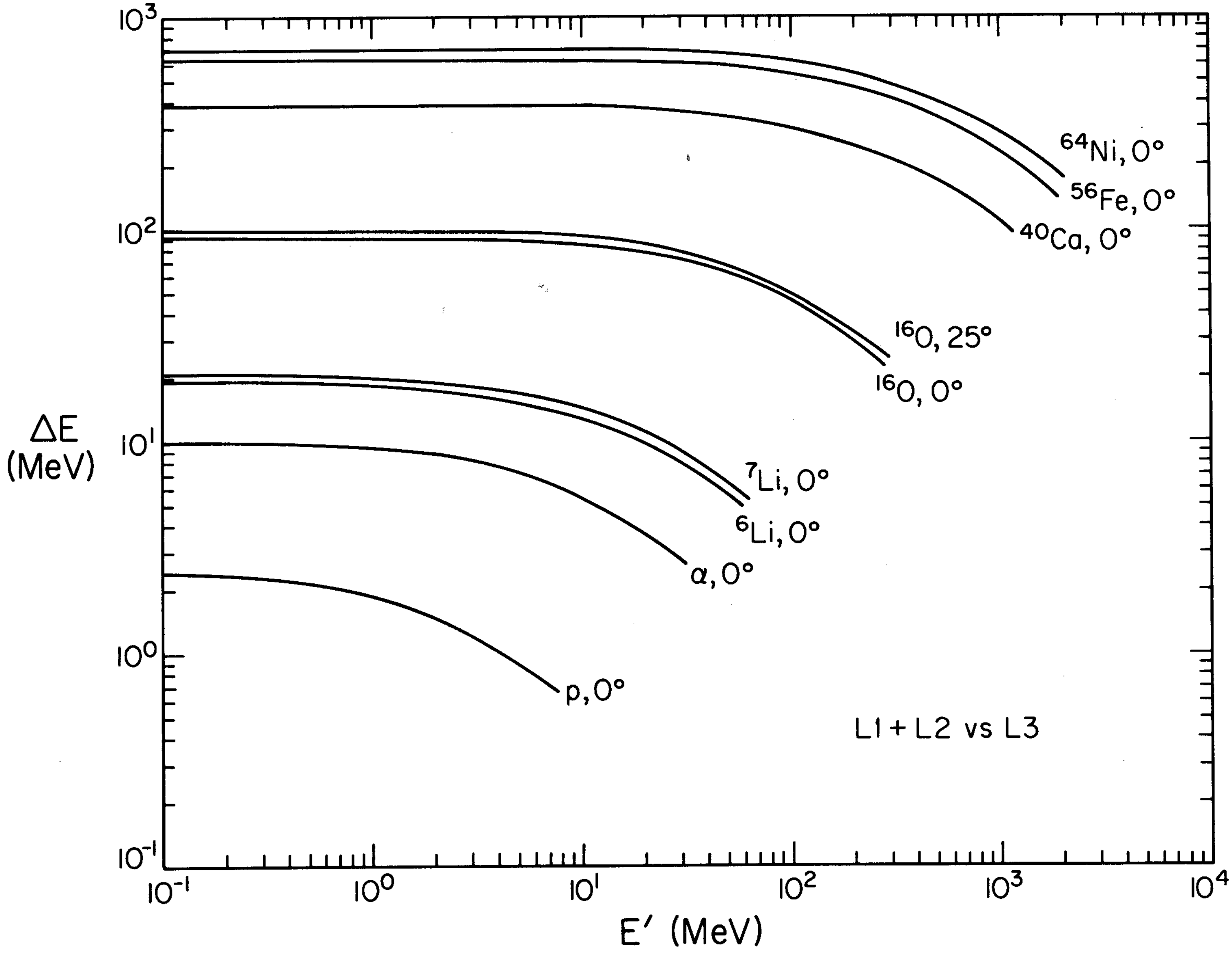
[1)] (L3) indicates that the L3 requirement can be implemented by command. SL indicates a slant threshold set between ^{4}He and ^{6}Li.

[2)] Rate information is available for each LET individually.



10^3
10^2
10^1
10^0
10^{-1}
ΔE (MeV)
10^{-1}
10^0
10^1
10^2
10^3
E′ (MeV)
^{64}Ni, 0°
^{56}Fe, 0°
^{40}Ca, 0°
^{16}O, 25°
^{16}O, 0°
^{7}Li, 0°
^{6}Li, 0°
α, 0°
p, 0°
L1 vs L2

Figure A8-3



^{64}Ni, 0°
^{56}Fe, 0°
^{40}Ca, 0°
^{16}O, 25°
^{16}O, 0°
^{7}Li, 0°
^{6}Li, 0°
α, 0°
p, 0°
L1 + L2 vs L3
ΔE (MeV)
E′ (MeV)
10^3
10^2
10^1
10^0
10^{-1}
10^{-1}
10^0
10^1
10^2
10^3
10^4

Figure A8-4

Figures A8-5 and A8-6 show the calculated mass resolution of the LET. The pathlength component σ_{PL} is clearly dominant. This term is due to uncertainty in angle of incidence and non-uniformity of detector thickness (0.5 microns). The Landau fluctuations in ΔE contribute (σ_{FL}) as do electronic uncertainties ($\sigma_{\delta E}$ and $\sigma_{E'}$) in ΔE and E'. These electronic uncertainties are due to noise and PHA channel width.

In addition, an "integral analyzer" has been connected to L1. This integral analyzer is a set of four discriminators set at thresholds of 0.45, 1.88, 7.5, and 75.7 MeV. Calculations based on power-law spectra ($dj/dE = kE^{-2}$) and normal cosmic-ray abundances show that in the first "channel," i.e., the energy loss region from 0.45 to 1.88 MeV which is predominantly protons, the signal-to-background ratio is 4.8. Signal is considered to be protons in the specified 0.45 to 1.88 MeV energy range, while protons with $E > 1.88$ MeV are considered background. For helium nuclei in the second channel (1.88 to 7.5 MeV), the signal to background ratio is 1.3. Oxygen is the most abundant element in the third channel, but signal/background is only 0.1 for the assumed spectra. If the "Oxygen excess" measured near Earth persists into interstellar space, this ratio will be > 1. See Figure A8-7. The primary advantage of the single parameter mode is the large geometrical factor (5 $cm^2 sr$) which permits determination of anisotropies of ∿1% in one month for spectra softer than E^{-2}.

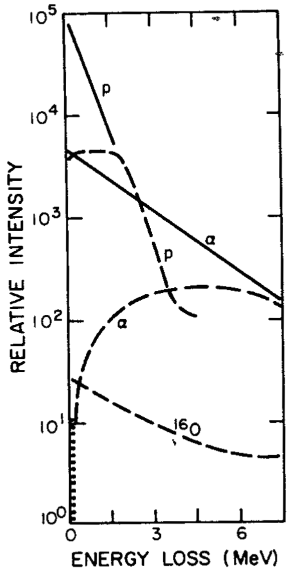


FIGURE A8-7: Energy-loss spectra for several nuclei are shown. These are calculated for the $\gamma = 2$ power-law spectra specified in the text. Solid lines are valid particles. Dashed lines background. The dotted line is due to very-high-energy protons.

NOTE: Figures A8-5 and A8-6 appear on the following pages.

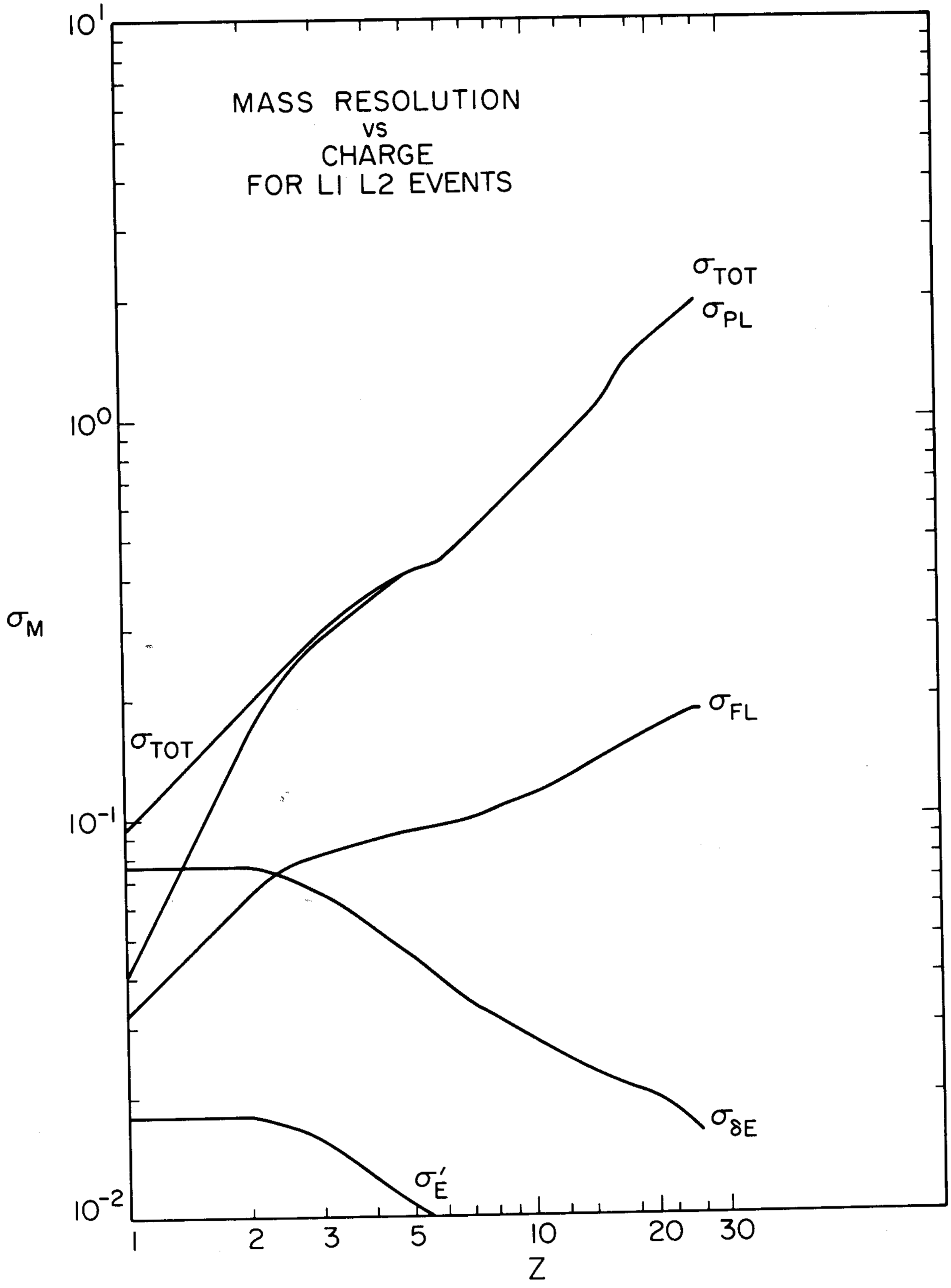

MASS RESOLUTION
VS
CHARGE
FOR L1 L2 EVENTS
σ_M
10^1
10^0
10^{-1}
10^{-2}
1
2
3
5
10
20
30
Z
σ_{TOT}
σ_{PL}
σ_{TOT}
σ_{FL}
$\sigma_{\delta E}$
σ'_E

Figure A8-5

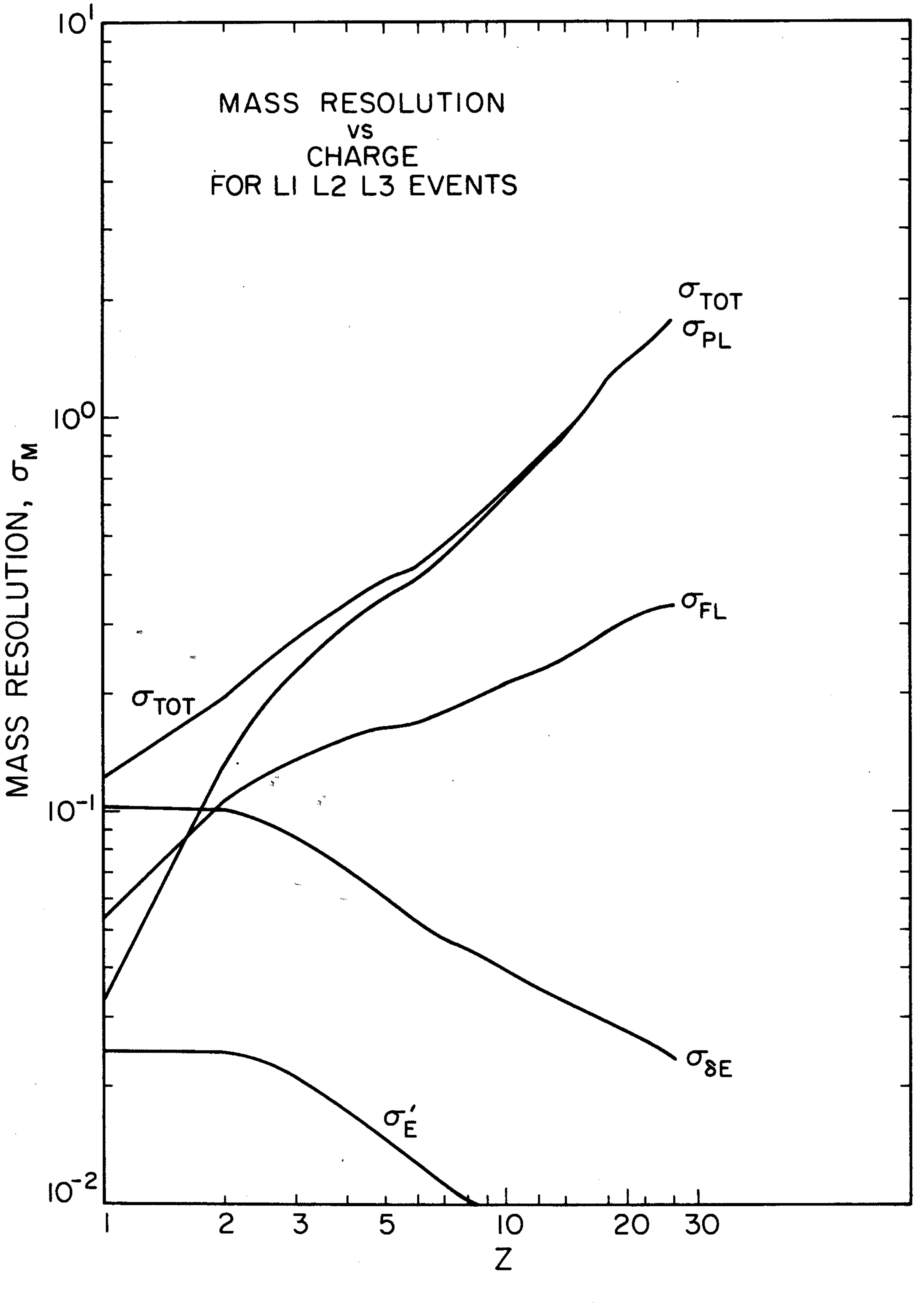
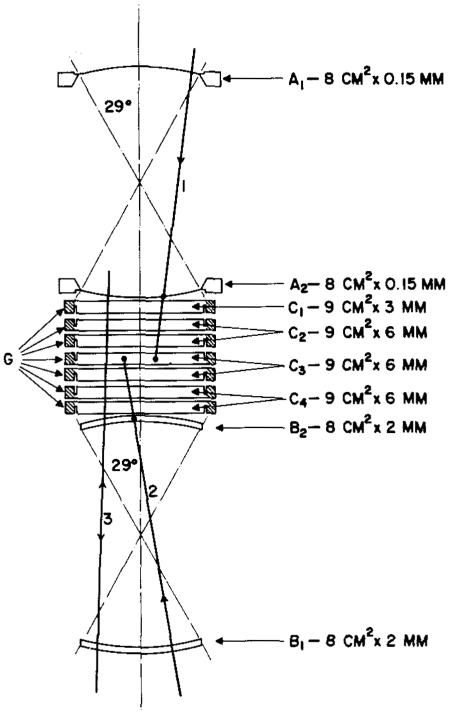

MASS RESOLUTION
vs
CHARGE
FOR L1 L2 L3 EVENTS
MASS RESOLUTION, σ_M
10^1
10^0
10^{-1}
10^{-2}
1
2
3
5
10
20
30
Z
σ_{TOT}
σ_{TOT}
σ_{PL}
σ_{FL}
$\sigma_{\delta E}$
σ'_E

Figure A8-6

APPENDIX A9

THE HIGH ENERGY TELESCOPE SYSTEM

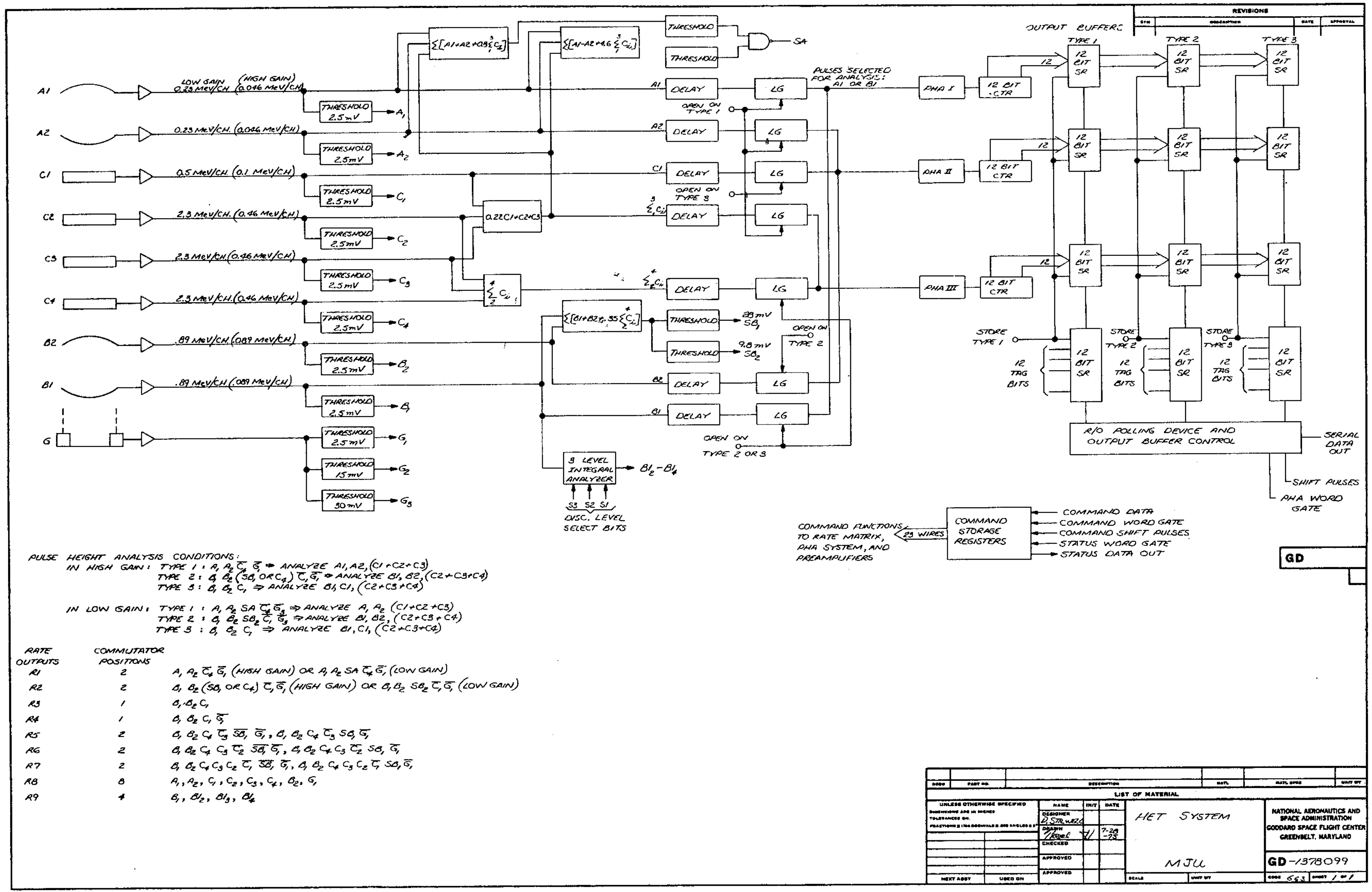
The High Energy Telescope System (HETS) consists of the double-ended telescope illustrated in Figure A9-1 and the electronics illustrated in Figure A9-2 (see Page A9-2). The HET telescope is a unique combination of solid-state detectors: A_1 and A_2 are curved surface barrier detectors, B_1 and B_2 are curved Li-drifted detectors, and C_1 through C_4 are the central areas of double-grooved Li-drifted detectors. The double grooves create annular detectors around each central area. The annular detectors taken together constitute an anti-coincidence or guard detector (denoted G) surrounding C_1 through C_4. A double-grooved detector is illustrated in Appendix A10. Accelerator tests indicate that cross talk between the central and annular areas is less than one part in 2,000. The A and B detectors are curved to minimize variations in particle path length in these detectors due to the finite telescope opening angle.



HIGH ENERGY TELESCOPE (HET)

Figure A9-1

Three classes of events are recognized by the electronics, two stopping (S_1 and S_2) and one penetrating (P). S_1 events are characterized by the coincidence condition $A_1A_2\overline{C_4}\,\overline{G}$. Trajectory 1 in Fig. A9-1 is a typical S_1 event. For particles stopping in A_2, detectors A_1 and A_2 operate in a dE/dx by E mode. For particles stopping in the C_1+C_2+C_3 stack, A_1 and A_2 provide double dE/dx measurements while C_1+C_2+C_3 measures the residual energy. For protons and alphas, S_1 events lie between 4 and 57 MeV/nuc. S_2 events, characterized by the coincidence condition $B_1B_2(SB_1 \text{ or } C_4)\overline{C_1}\,\overline{G}$ are analogous to the S_1 events, except that the coincidence condition includes the term (SB_1 or C_4) which is incorporated to reject RTG-produced Compton electrons. Trajectory 2 in Figure A9-1 is a typical S_2 event. The thicker dE/dx elements, B_1 and B_2, are less subject to Landau fluctuations at high energies than the thinner elements A_1 and A_2. On the other hand, they cause S_2 events to have a higher threshold energy (18 MeV) than the S_1 events (4 MeV). Residual energy measurements are made in C_2+C_3+C_4 for S_2 events. For protons and alphas the S_2 mode corresponds to 18-70 MeV/nucleon. Electrons between $\sim$3 and 12 MeV will also be measured in the S_2 mode. Finally, P events are events which penetrate the whole telescope and satisfy the coincidence condition $B_1B_2C_1$. In this mode detectors B_1, C_1 and C_2+C_3+C_4 are pulse-height analyzed. The P mode extends spectral measurements to $\sim$500 MeV/nucleon and also allows an integral measurement above this energy. In the P mode, because of the problem of knock-on electrons, the G detector is not used to reject events, but to tag them. It may be noted in Figure A9-2 that the G detector is in fact level discriminated at three different levels; this provides an additional precaution against cross-talk.



PULSE HEIGHT ANALYSIS CONDITIONS:

IN HIGH GAIN:
TYPE 1 : $A_1 A_2 \overline{C}_4 \overline{G}_1$ ⇒ ANALYZE A1, A2, (C1+C2+C3)
TYPE 2 : $B_1 B_2 (SB_1 \text{ OR } C_4) \overline{C}_1 \overline{G}_1$ ⇒ ANALYZE B1, B2, (C2+C3+C4)
TYPE 3 : $B_1 B_2 C_1$ ⇒ ANALYZE B1, C1, (C2+C3+C4)

IN LOW GAIN:
TYPE 1 : $A_1 A_2 SA \overline{C}_4 \overline{G}_1$ ⇒ ANALYZE A1, A2 (C1+C2+C3)
TYPE 2 : $B_1 B_2 SB_2 \overline{C}_1 \overline{G}_1$ ⇒ ANALYZE B1, B2, (C2+C3+C4)
TYPE 3 : $B_1 B_2 C_1$ ⇒ ANALYZE B1, C1, (C2+C3+C4)

RATE OUTPUTS	COMMUTATOR POSITIONS	
R1	2	$A_1 A_2 \overline{C}_4 \overline{G}_1$ (HIGH GAIN) OR $A_1 A_2 SA \overline{C}_4 \overline{G}_1$ (LOW GAIN)
R2	2	$B_1 B_2 (SB_1 \text{ OR } C_4) \overline{C}_1 \overline{G}_1$ (HIGH GAIN) OR $B_1 B_2 SB_2 \overline{C}_1 \overline{G}_1$ (LOW GAIN)
R3	1	$B_1 B_2 C_1$
R4	1	$B_1 B_2 C_1 \overline{G}_1$
R5	2	$B_1 B_2 C_4 \overline{C}_3 \overline{SB_1} \overline{G}_1$, $B_1 B_2 C_4 \overline{C}_3 SB_1 \overline{G}_1$
R6	2	$B_1 B_2 C_4 C_3 \overline{C}_2 \overline{SB_1} \overline{G}_1$, $B_1 B_2 C_4 C_3 \overline{C}_2 SB_1 \overline{G}_1$
R7	2	$B_1 B_2 C_4 C_3 C_2 \overline{C}_1 \overline{SB_1} \overline{G}_1$, $B_1 B_2 C_4 C_3 C_2 \overline{C}_1 SB_1 \overline{G}_1$
R8	8	$A_1, A_2, C_1, C_2, C_3, C_4, B_2, G_1$
R9	4	$B_1, B1_2, B1_3, B1_4$

Figure A9-2

In order to accomodate the very large ranges in particle charge and energy, effective electronic dynamic ranges of up to 40,000 are required. This is accomplished using 4096-channel pulse-height analyzers and preamplifiers with two gain modes, high gain and low gain, differing in gain by factors of 5 or 10 (see Figure A9-2). Nuclei with charge $Z > 2$ are analyzed in both gain modes. In low gain mode, however, protons and alphas are not recognized as S_1 events, electrons and protons are not recognized as S_2 events and protons are excluded from P events. Figure A9-2 shows that there exist storage registers for storing pulse-height data for S_1, S_2 and P events separately. A read-out polling device samples and reads out data for each event type in sequence, skipping an event type only if its registers are empty. Combined with the gain-mode switching, this results in a priority system for data read-out.

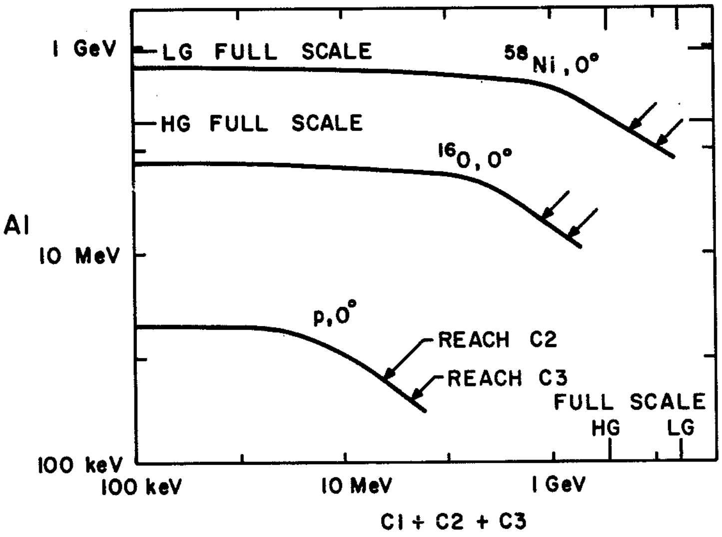
The excellent charge and isotopic resolution for S_2 events is discussed in Appendix A10. In Table A9-1 we illustrate the charge and isotopic resolution for S_1 events:

TABLE A9-1: HET S_1 RESOLUTION

ISOTOPE	ENERGY (MeV/NUCLEON)	CHARGE SEPARATION (IN UNITS OF σ_Z)	ISOTOPE SEPARATION (IN UNITS OF σ_A)
O^{16}	69 (mid-range)	15	2.1
	52 (exit C_1)	17	2.4
Be^{10}	41 (mid-range)	24	2.7
Fe^{56}	131 (mid-range)	6.3	---

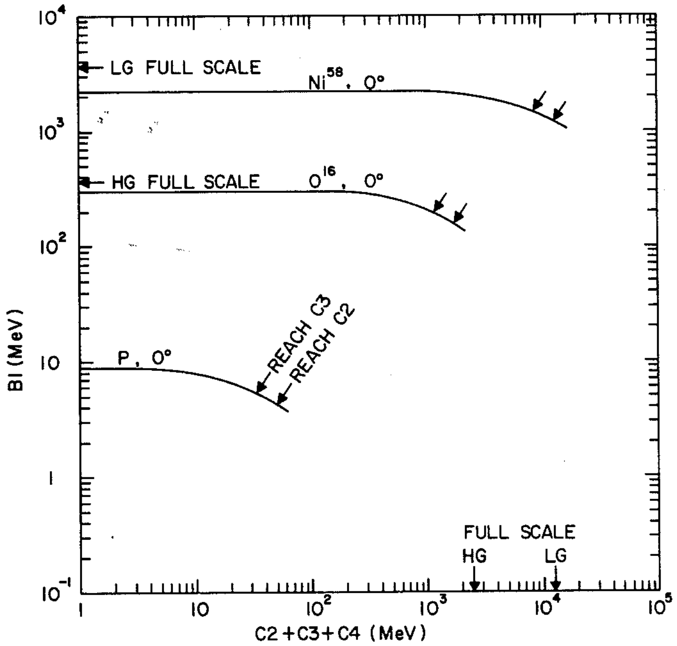
We see that isotopes may be reasonably well resolved up through oxygen and that individual charges are easily resolved through iron. Isotopes will not be resolvable in the P mode.

Curves illustrating the response of HETS for both S_1 and S_2 events in the double dE/dx by E mode are shown in Figures A9-3 and A9-4 (see Page A9-4).



ΔE vs E FOR HET S_1 EVENTS

Figure A9-3



ΔE vs. E FOR HET S2. EVENTS

Figure A9-4

APPENDIX A10

DETECTOR RESOLUTION AND BACKGROUND

In this appendix we describe the considerations necessary to achieve the high resolution and low background required by our experiments. Resolution in a pulse-height matrix refers to the percentage width of the response curve for any given type of particle and thus is a measure of the ability to separate and identify different particle types. By background in a pulse-height matrix we refer to any distribution of events which contributes events to areas of the matrix where ideally there would be no events. Such a distribution also adds events to the areas of ideal response which are thus undistinguishable from the desired events. In general one must estimate the number of such events and make a background subtraction. Such corrections, if significant, will be reduced if the resolution is improved.

Monoenergetic particles of charge Z and mass A entering a dE/dx x E telescope give rise to Gaussian response distributions in the dE/dx and E dimensions. The charge Z and mass A are functions of the mean dE/dx and E responses. Thus the Gaussian response distributions in the dE/dx and E dimensions (with standard deviations $\sigma_{\frac{dE}{dx}}$ and σ_E) give rise to Gaussian distributions in the experimental charge and mass dimensions (with standard deviations σ_Z and σ_A). With the help of Goulding's approximation (Range $\propto \frac{A}{Z^2} \left(\frac{E}{A}\right)^{\gamma}$ it is straightforward to demonstrate that

$$\sigma_Z \approx \frac{1}{\gamma+1} \sqrt{(\gamma-1)^2 \sigma_E^{\,2} + \sigma_{\frac{dE}{dx}}^{\,2}} \tag{1}$$

and

$$\sigma_A \approx \sqrt{\sigma_E^{\,2} + \left(\frac{1}{\gamma-1}\right)^2 \sigma_{\frac{dE}{dx}}^{\,2}}\ , \tag{2}$$

where $\gamma \approx 1.77$ for Silicon and the standard deviations are to be expressed in %. (1) and (2) imply

$$\sigma_A \approx \left(\frac{\gamma+1}{\gamma-1}\right) \sigma_Z\ , \tag{3}$$

from which it is apparent that isotopes are more difficult to resolve than charges. The separation between adjacent charge (mass) peaks in % is given $\frac{1}{Z}$ x 100% ($\frac{1}{A}$ x 100%).

Let us now consider the factors which determine $\sigma_{\frac{dE}{dx}}$ and σ_E. We consider $\sigma_{\frac{dE}{dx}}$ first since frequently it dominates σ_E. Contributors to $\sigma_{\frac{dE}{dx}}$ are non-uniformity of detector thickness, path length distribution, preamplifier noise, Landau statistics, and digitization error.

The amount of energy deposited by a particle penetrating through a detector depends on the length of the particle path in the detector. Thus non-uniformity of the detector thickness will affect the amount of energy deposited in the detector. Similarly, different angles of the path with respect to the telescope axis will give rise to different path lengths and thus to a distribution of energy losses. The use of curved detectors minimizes this effect. The optimum radius of curvature is obtained following Perkins et al. (1969). Preamplifier noise is a constant contributor and will be important primarily for protons. Digitization errors are negligible. For example, we use 4,000 channel analyzers for the HETS. Finally, Landau broadening occurs because the energy loss process is subject to statistical fluctuations; this effect may be readily calculated (e.g., Clarke, 1971). $\sigma_{dE/dx}$ is then determined by quadratically adding the standard deviations for each of the above effects.

σ_E in a stack of Li-drifted solid-state detectors as in HET arises from preamplifier noise and the presence of so-called dead layers. The effects of such layers have been considered by Greiner (1972). We make deliberate efforts to keep these layers less than 80μ thick.

As an example, we indicate in Table A10-1 the expected resolution for the S_2 mode of the HET:

TABLE A10-1: HET S_2 RESOLUTION

ISOTOPE	(MeV/nucleon)	Charge Separation (in units of σ_Z)	Isotope Separation (in units of σ)
^{16}O	153 (end-point)	19	2.6
	106 (mid-range)	20	2.8
^{10}Be	91 (end-point)	24	2.7
	63 (mid-range)	29	3.3
^{56}Fe	295 (end-point)	8	1.1

The entries for ^{16}O and ^{10}Be illustrate the fact that the resolution improves with decreasing energy as the Landau fluctuations decrease. We see that over the full range of energies and up through the isotopes of oxygen, the separation between isotopes is greater than 2.6 standard deviations.

Detector background is predominantly produced by particles which undergo catastrophic nuclear interactions within the residual E detector. Low-energy secondary products can be produced which exit through the dE/dx elements and masquerade as heavy particles. A redundant dE/dx measurement is an extremely valuable tool in rejecting this kind of background. Such slow moving secondary products would, in general, not be expected to produce identical outputs in the dE/dx elements and would be eliminated by the application of a consistency criterion. Evidence in support of this conclusion is shown in Fig. A10-1. This is data taken from the Goddard - Univ. of New Hampshire cosmic ray experiment on the Pioneer 10 spacecraft. The pioneer 10 telescope is similar to the MJS/MJU HET, with the one important exception that no guard-ring detectors were used. Background on Pioneer 10 is rejected only by the use of double-dE/dx and range criteria. The data shown is a plot of the output of the front element vs. the output of the stack. The prominent line is due to quiet-time alpha particles. The signal-to-background ratio in this data is remarkably good. ^3He and ^4He will be easily resolvable. Also the light element region above the alpha line is almost completely background free. We emphasize that our MJS/MJU High-Energy Telescope will be significantly better than this due to the use of guard ring detectors (cf. Fig. A10-2).

Background in the electron response region of the HET arises due to the Radioactive Thermonuclear Generators (RTGs) on board. This is discussed in detail in Appendix A12.

References:

Clarke, N. M. Nuc. Instr. and Meth. <u>96</u>, 497, 1971.
Greiner, D. E., Nuc. Instr. and Meth. <u>103</u>, 291, 1972.
Perkins, M. A., Kristoff, J. J., Mason, G. M. and Sullivan, J. D., Nuc. Instr. and Meth. <u>68</u>, 149, 1969.

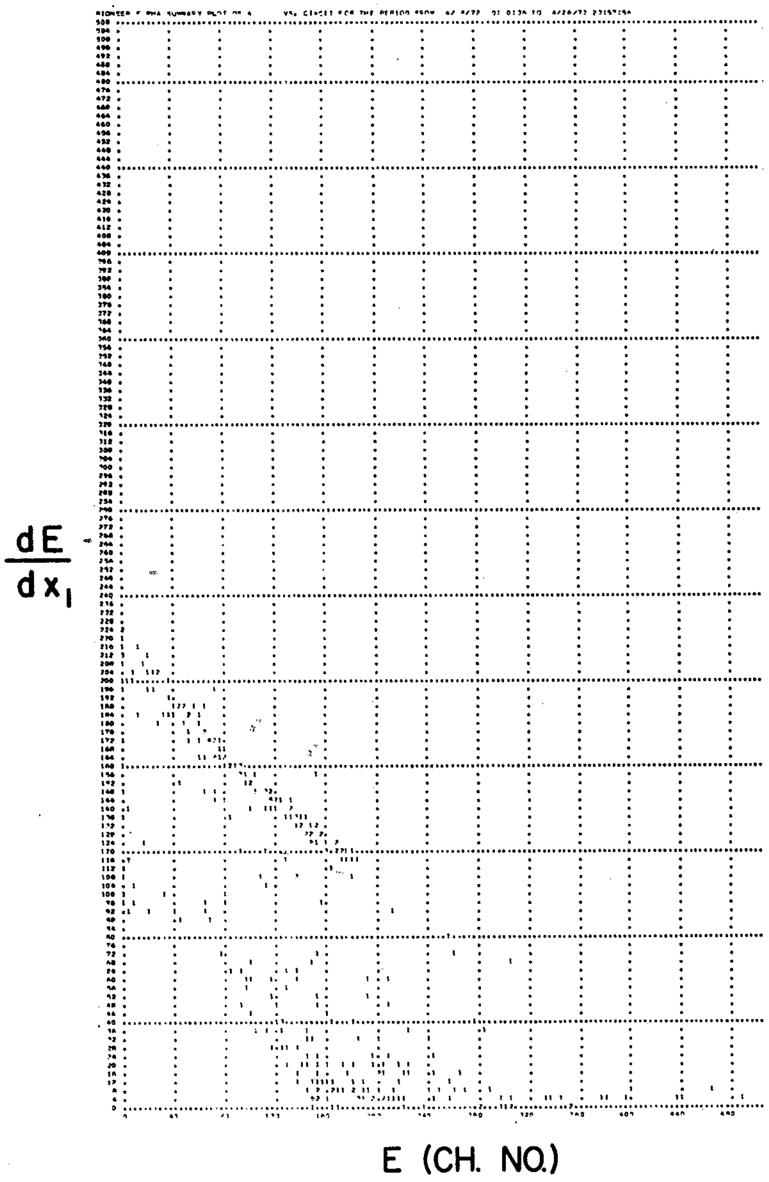


FIGURE A10-1

PIONEER 10 dE/dx VS. E DATA

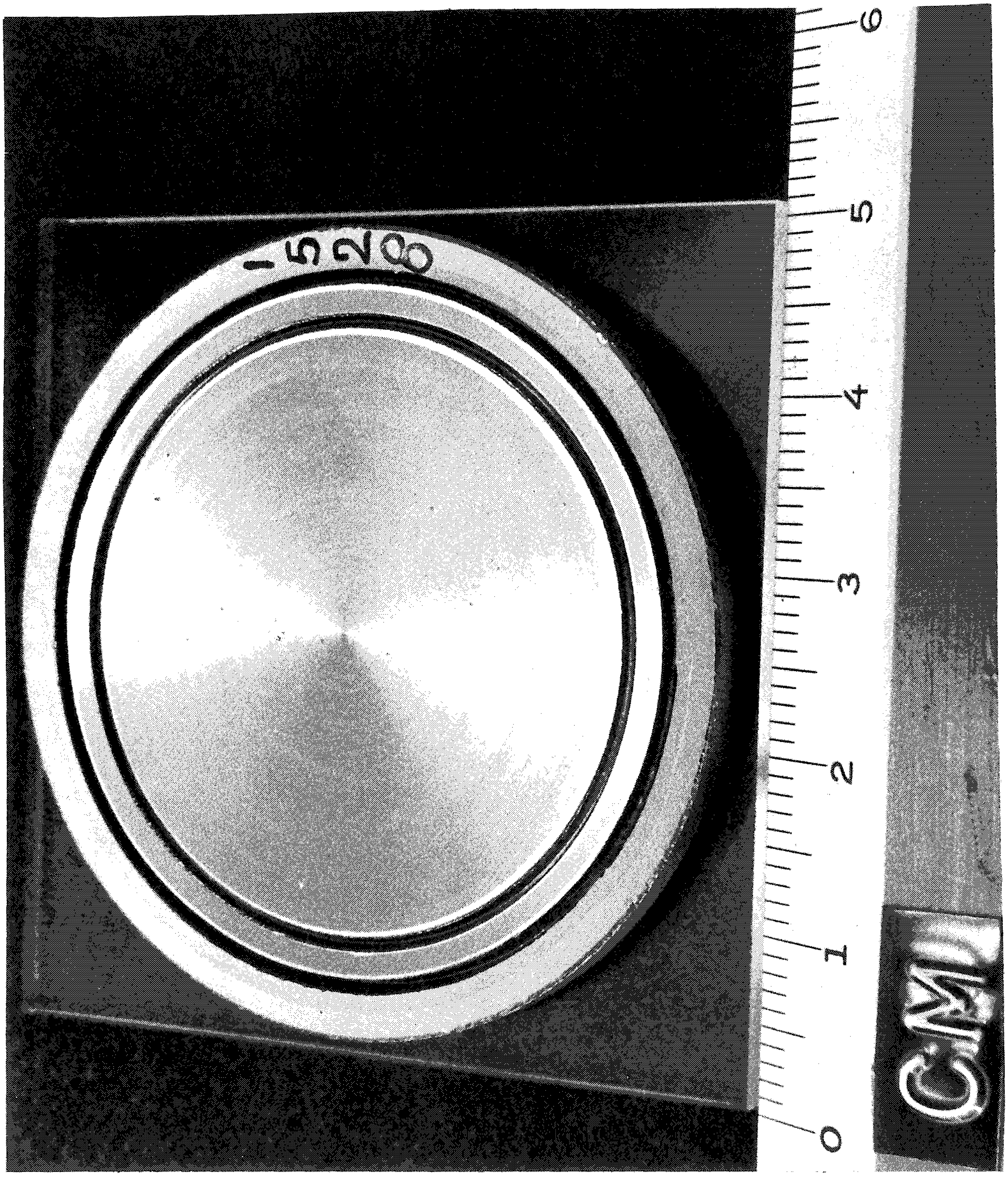


FIGURE A10-2
GUARD RING DETECTOR

APPENDIX A11

INSTRUMENTATION

A11.1 SYSTEM NOISE CONSIDERATIONS

In designing the detector and electronic system in such an experiment, one is always faced with situations which require trade-offs between the observed noise, the shaping time constants, the high-count-rate performance and the desired threshold level. For lowest overall noise performance, one would select unipolar pulse shaping and dc coupling throughout. However, unipolar pulse shaping leads to significant baseline shift and therefore distortion at high count rates, and dc coupling leads to equally bad compensation and drift problems. One therefore usually generates bipolar pulses using either CR-CR shaping or delay line shaping.

Delay line shaping is useful where the detector signal is above the amplifier noise and where a large dynamic range is not required. It is particularly useful for the signal shaping for the sensors within the MTA where the pulses are clipped at 150 ns. In the case of the HET, LET and ELET telescopes, noise on signal lines is often dominated by amplifier noise due to very large detector capacitance ($C_D \sim 200 - 900$ pf). Additionally, a large linear dynamic range greater than 4096 is required. In this case we have chosen pulse shaping consisting of double differentiation and integration with equal time constants of $\sim 1 \mu$sec.

This 1μsec time constant is longer than desired for optimum signal-to-noise for Li-drifted detectors, but shorter than optimum for the high capacitance surface barrier detectors. However, the performance is more than adequate in all cases, and a significant advantage results from the use of identical time constants throughout. It allows the standardization of circuitry, testing and use of the pulse-height analyzer.

A11.2 PULSE PILE-UP

Owing to the random rate at which charged particles enter a given detector, there is always a finite possibility that two particles may enter in rapid succession. The probability is higher at higher count rates, obviously, and is a major concern in the design of such sensor systems. Since the output pulse of any amplifier has a finite duration, there is a possibility that two pulses will overlie one another or "pile-up." In this case, the threshold circuit or pulse-height analyzer will not see the pulses at their true height. To minimize these effects, the output pulse should be as short as possible and return to zero as soon as possible. As pointed out in Section A11.1 of this appendix, this was a major design driver in selecting bipolar pulse shaping with fast time constants for the MTA.

In calculating n-fold pile-up rates, the following formula by Fillius (1963) is used:

$$R_n = R_1 \left[1 - e^{-\tau R_1} \left(1 + R_1 \tau + \frac{(\tau R_1)^2}{2} + \ldots \frac{(\tau R_1)^{n-2}}{(n-2)!} \right) \right]$$

where R_n is the rate at which n-fold pile-ups are occurring and τ is the resolving time. In addition to the spectral distortion discussed in the previous paragraph, one has to be concerned about the individual rates used for normalizing the spectra. Many times in any such experiment the τ of the shaping circuit determines the pulse pile-up, but the dead time of the threshold circuit limits the apparent count rate. One has to take great care in the design of such systems, therefore, when one expects to operate at high count rates.

A11.3 REDUNDANCY AND RELIABILITY

In the main proposal, we have developed our reasoning for deciding to use multiple sensors in order to measure the particle distributions and anisotropies. Phenomena were seen at Jupiter by the Pioneer 10/11 experiments which had time scales $\lesssim$ the spacecraft spin period of 12 seconds. It is physically important to know that these phenomena are occurring; and we feel that multiple detectors viewing different directions and simultaneously recording the data on time scales $\leq$ 6 seconds are necessary. If the design shares one counting register amongst several detectors, this can lead to ambiguity between temporal changes and anisotropies. If one uses a sensor mounted on a mechanical rotation device, it must cycle very rapidly and reliably for many years. This is a major disadvantage for the approach using the rotation device. Such electromechanical devices have in general proven to be far less reliable than conventional electronics systems.

Our chosen approach, on the other hand, has the advantage of redundancy. The directional telescopes of MTA and LETS have 4-fold redundancy while those of HET and ELET have effectively 2-fold redundancy. Should a problem occur in the 6+ years of flight time, there are several options available by command. An entire telescope can be shut down, or an individual detector can be removed from the set by commanding off its preamplifier(s). In many cases we are able to reprogram the logic equation for the pha conditions and the corresponding rates. Additionally, the experiment and spacecraft data systems are very flexible and allow a wide variety of data formats, mixtures of pha and rate data and bit rates. The data system design also emphasizes many parallel paths and a very minimum of shared paths.

A11.4 PARTS, FABRICATION AND RADIATION DAMAGE

The parts and parts program proposed for this program provide our conventional high-reliability items which we have used for both Pioneer 10/11 and MJS. Extensive testing and analysis by both JPL and the MJS experiment team have shown that the most radiation-sensitive parts within the experiment are the JPL-supplied CMOS parts which are in all experiments and subsystems. We are just now receiving these parts, but they appear to allow a substantial margin against the worst-case radiation at Jupiter. In addition to the CMOS, this experiment makes large use of a custom-designed LSI PMOS circuit (AMI 1375) known affectionately as a "Mars bug." This device has a radiation tolerance of ∿600 K rads, superior to the CMOS and well in excess of the expected dose at Jupiter of ∿100-150 K rads. Additionally, the mechanical design of the experiment provides for mounting the data systems "inside" the other electronic systems, providing much more shielding than expected from the sidewalls, honeycomb plate and thermal blankets themselves.

Although many of this experiment's ∿100,000 transistors are in the LSI circuitry within the data systems, a huge number of discrete components are packaged in a relatively-small amount of weight in the preamplifiers, amplifiers, pulse logic and pulse-height analysis systems. Most of this circuitry is packaged in a hybrid form using semiconductors in small ceramic packages which in turn are mounted on ceramic substrates which include the conductors, resistors, etc. This techniqe is well proven, having been used for Pioneer 10/11, IMP H/J, Helios A/B and MJS.

A11.5 POWER SUMMARY

HET/LET preamplifier/amplifier	1.02 watts
HET PHA System	.39
LET PHA System	.46
MTA System	2.30
ELET System	.28
Data System	.65
Detector Bias Supplies	.25
	5.35 watts
Raw Power @ 78% Efficiency:	6.8 watts

A11.6 WEIGHT SUMMARY

HET and preamp/amps	494
LET and preamp/amps	488
ELET and electronics	300
MTA sensors	400
MTA electronics	1300
HETS pha system	643
LETS pha system	864
Data system with shielding	1082
Power Supply	300
Mechanical system	866
Interconnect	370
TOTAL:	7102 grams

A11.7 MOUNTING

The package mounts on the spacecraft in exactly the same fashion as the CRS experiment on MJS.

Reference: Fillius, R.W., University of Iowa Preprint 63-26, August 1963.

APPENDIX A12

RTG γ-RAY BACKGROUND

The proposed HET telescope covers the differential energy spectrum of electrons in the nominal energy range of ~ 2 - 10 MeV. The HET, like any electron sensor in this energy range, is significantly affected by a background due to intense γ-ray fluxes from the RTG spacecraft power source. We have studied the RTG induced electron background by computer modeling, and we have verified the results directly by comparison with this group's electron detectors on the Pioneer 10 & 11 missions. We are satisfied that we understand the RTG effects, which in effect set intensity thresholds for the measurement of primary electron fluxes.

The RTG γ-ray induced background in HET is due to Compton electrons produced by γ-rays in the solid state detectors of the telescope (Figure A12-1). For example, a Compton electron produced in detector C4 with sufficient energy and the proper trajectory could penetrate B2 and deposit the correct amount of energy in B1 and C4 to satisfy the triple coincidence requirement B1•B2•C4 with the correct electron signature. Similarly, Compton electrons produced in C3 and C2 may penetrate to B1 to cause 4-fold or 5-fold coincidences respectively.

As an illustrative example, we shall analyze the effects of RTG produced free field γ-rays upon the CRS HET telescope (identical to the HET proposed for MJU) on the MJS77 mission. The MJS77 RTG γ-ray spectrum at HET is shown in Figure A12-2. Using this γ-ray spectrum and the known Compton cross-sections, we have calculated the Compton electron production in the HET detector material (Si), as shown in Figure A12-3. Note, that the Compton electron spectrum above ~ 2.3 MeV drops by ~ 3 orders of magnitude, due to the corresponding drop in the γ-ray intensity above the 2.6 MeV $T\ell^{208}$line. Clearly, the RTG background is most significant at lower energies.

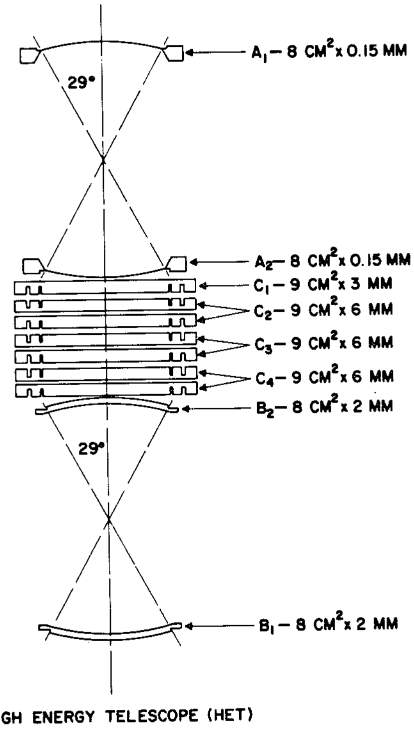
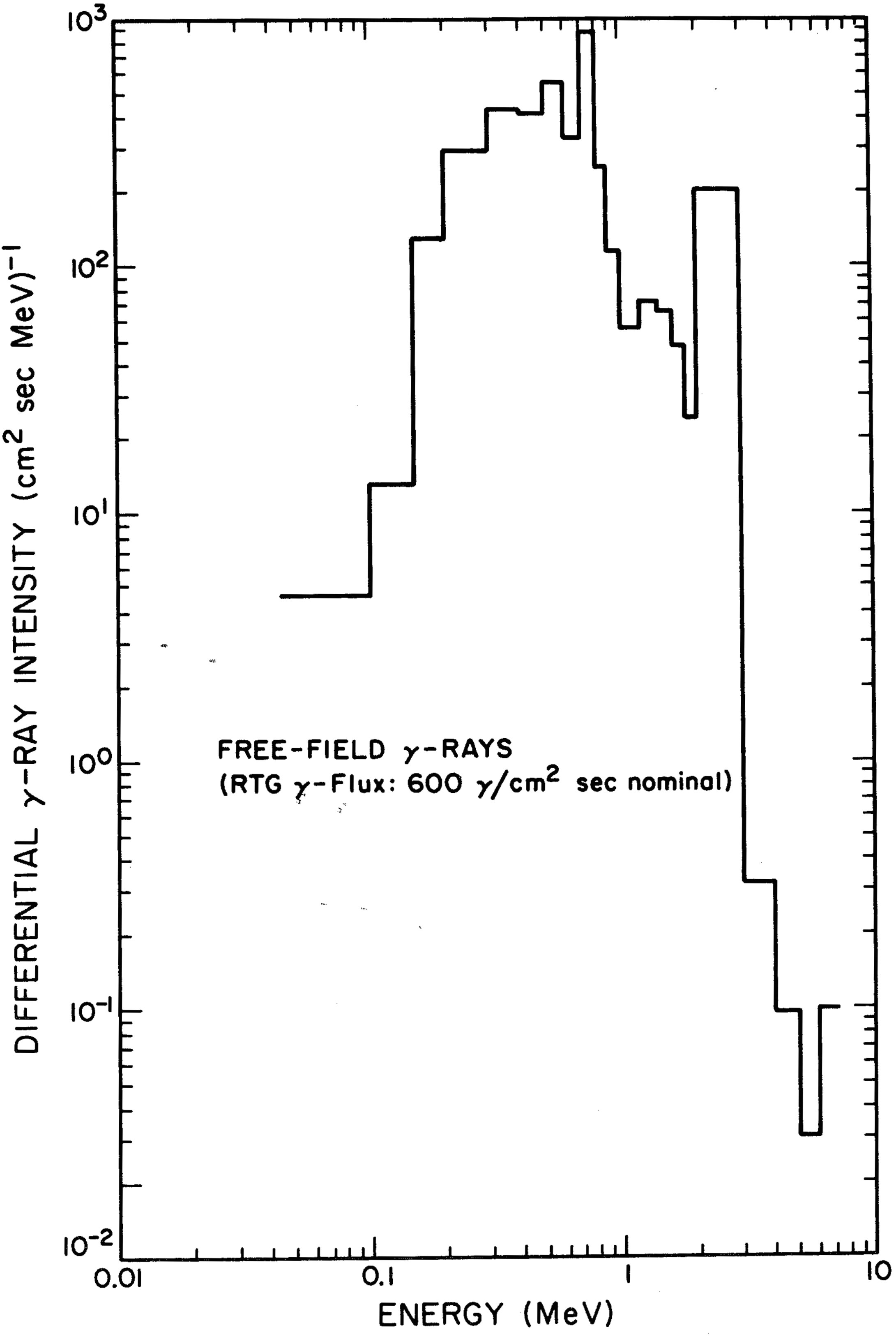


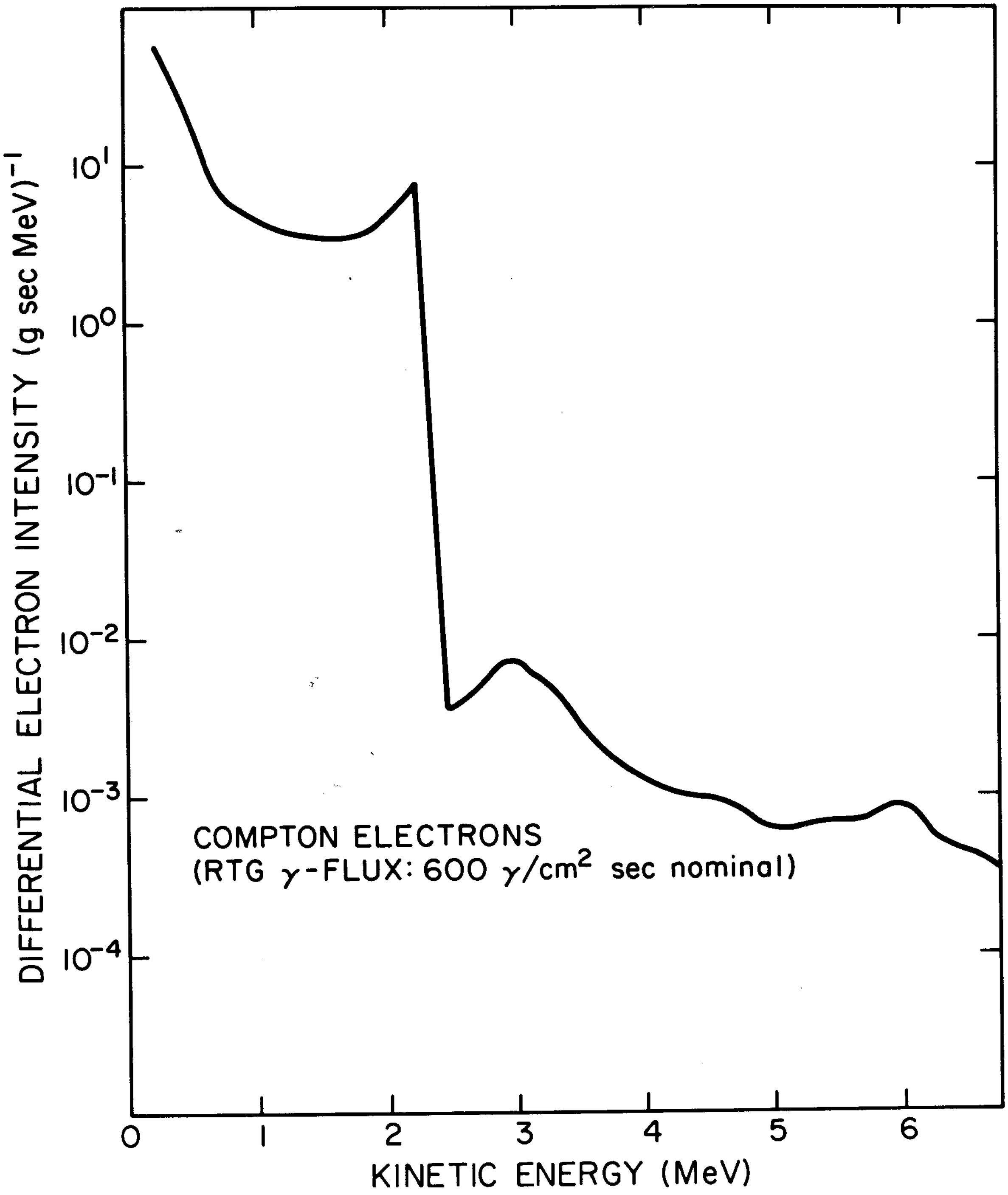
Figure A12-1

We have calculated the expected HET 3, 4, and 5-fold Compton electron coincidence rates as follows:



DIFFERENTIAL γ-RAY INTENSITY (cm² sec MeV)⁻¹
10³
10²
10¹
10⁰
10⁻¹
10⁻²
0.01
0.1
1
10
ENERGY (MeV)
FREE-FIELD γ-RAYS
(RTG γ-Flux: 600 γ/cm² sec nominal)

Figure A12-2



DIFFERENTIAL ELECTRON INTENSITY (g sec MeV)$^{-1}$
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
COMPTON ELECTRONS
(RTG γ-FLUX: 600 γ/cm^2 sec nominal)
0
1
2
3
4
5
6
KINETIC ENERGY (MeV)

Figure A12-3

$$\text{Rate }(B1\cdot B2\cdot Ci) = \left[\int_{E_{min}}^{E_{max}} dE\ \frac{dJ}{dE}\right] \cdot M_{c_i} \cdot P(i) \qquad (1)$$

where

i = 4, 3, or 2 corresponds to 3, 4, or 5-fold coincidences

E_{min} = approximate minimum electron kinetic energy required for a B1. . . Ci event

E_{max} = 7 MeV, the upper limit of the Compton electron spectrum

$\frac{dJ}{dE}$ = Compton electron intensity (electrons/MeV sec g) from Figure 3

M_{c_i} = 12.5 grams, the mass of a C detector element

$P(i)$ = probability of Compton electrons produced in the detector with energy $> E_{min}$ satisfying the coincidence requirement

For simplicity, we have assumed (1) that the angular distribution of Compton electrons is that of a uniform distribution of point sources, (2) that all electrons follow straight line trajectories, and (3) that all electrons with $E > E_{min}$ and having trajectories that intersect B1 satisfy the coincidence requirements. In this model, P(i) depends only on geometry and is derived from a Monte Carlo calculation.

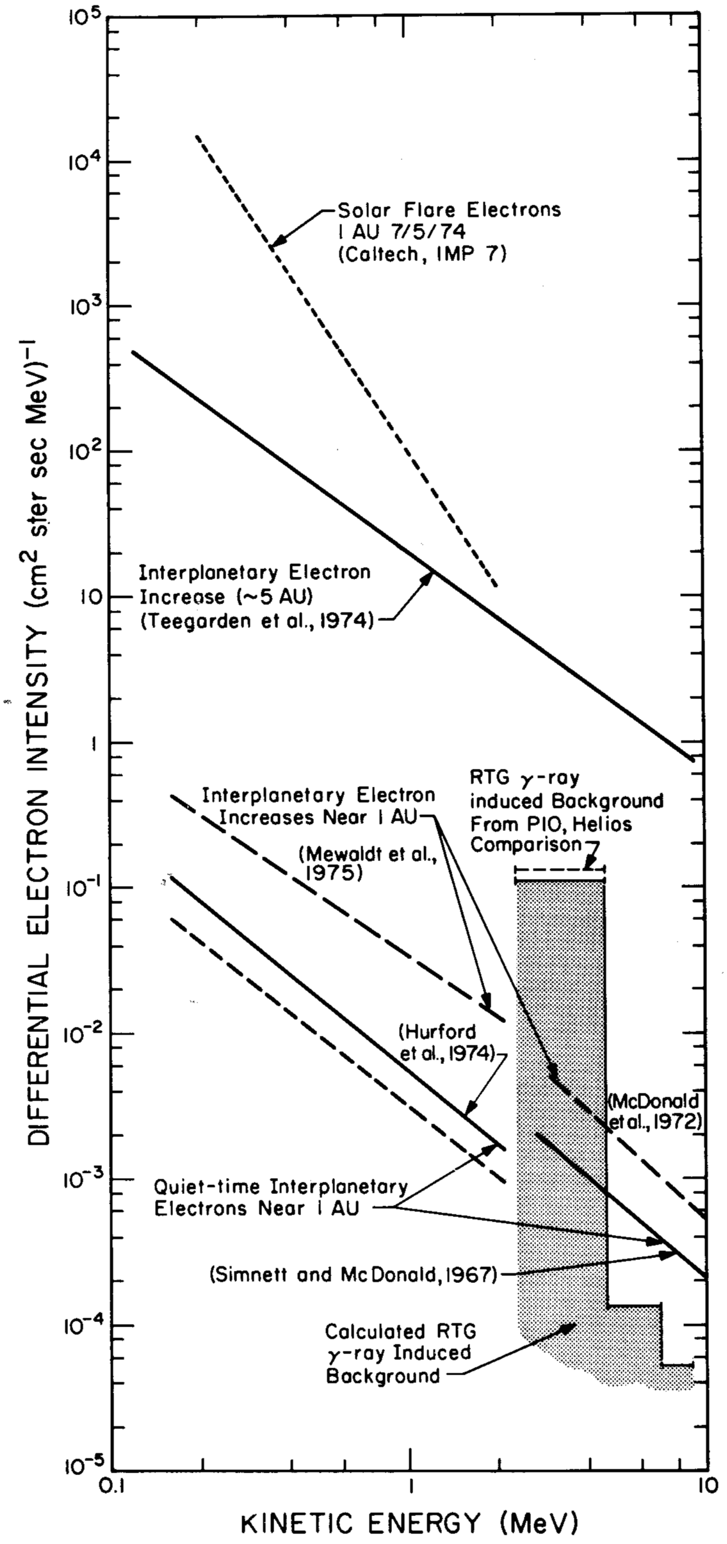
Table A12-1 lists the relevant parameters for equation (1) as applicable to HET, and the calculated RTG-γ-ray induced background electron count rates for the three HET coincidence conditions.

TABLE A12-1: RTG-γ-Ray Electrons in HET

Coincidence type	Emin (MeV)	$\left[\int_{E_{min}}^{E_{max}} dE\ \frac{dJ}{dE}\right]$ (e/g-sec)	P	Rate (e/sec)
3-fold	1.8	2.2	0.013	0.37
4-fold	3.6	2.8×10^{-3}	0.011	3.9×10^{-4}
5-fold	5.4	9.8×10^{-4}	0.009	1.1×10^{-4}

The validity of this calculation has been verified against an empirical derivation of electron background based upon the behaviour of similar telescopes of this group on the Pioneer 10 (with RTG) and the Helios (no RTG) spacecraft. This comparative study predicts, e.g., a 3-fold coincidence rate for HET of ~ 0.44/sec, compared to the result of 0.37/sec from the computer model calculation.

The rates from Table A12-1 have been converted to equivalent electron intensities and are plotted in Figure A12-4 as a histogram over the nominal energy range of HET. Figure A12-4 also shows, for comparison, typical quiet-



10^5
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
0.1
1
10
DIFFERENTIAL ELECTRON INTENSITY (cm^2 ster sec MeV)^-1
KINETIC ENERGY (MeV)
Solar Flare Electrons 1 AU 7/5/74 (Caltech, IMP 7)
Interplanetary Electron Increase (~5 AU) (Teegarden et al., 1974)
Interplanetary Electron Increases Near 1 AU
(Mewaldt et al., 1975)
RTG γ-ray induced Background From P10, Helios Comparison
(Hurford et al., 1974)
(McDonald et al., 1972)
Quiet-time Interplanetary Electrons Near 1 AU
(Simnett and McDonald, 1967)
Calculated RTG γ-ray Induced Background

Figure A12-4

time electron spectra observed near 1 AU (Hurford, G. J., R. A. Mewaldt, E. C. Stone, and R. E. Vogt, Ap. J. 192, 54, 1974; Simnett, G. M. and F. B. McDonald, Ap. J. 157, 1435, 1969). In addition, Figure A12-4 also shows a typical interplanetary electron spectrum during a period of enhanced intensity measured near 5 AU on Pioneer 10 (Teegarden, B. J., F. B. McDonald, J. H. Trainor, W. R. Webber, and E. C. Roelof, JGR 79, 3615, 1974), typical quiet-time increases near 1 AU (McDonald, F. B., T. L. Cline, and G. M. Simnett, JGR 77, 2213, 1972; Mewaldt, R. A., E. C. Stone and R. E. Vogt, Proc. 14th Int. Cosmic Ray Conf., Munich, OG 10-3, 1975), and a representative solar flare electron spectrum observed with Caltech's EIS on IMP-7.

At energies $E < 5$ MeV, the RTG background dominates the 1 AU quiet-time electron spectrum, but not the electron increases $\gtrsim 0.2/\text{cm}^2$ sec sr MeV as typical for quiet-time increases or solar flare electrons (see Figure A12-4). At higher energies, the RTG background is smaller than even the 1 AU quiet-time minimum electron intensities, allowing their observation essentially at all times.

Further reductions of the RTG electron background could occur on MJU79 from a conceivable modification of the respective orientation of RTG and HET or from changes in the RTG fuel. Other improvements, e.g., from HET shielding, the introduction of gas Cerenkov counters or time of flight features would be extremely costly in terms of weight and reliability, and less effective than at higher energies (due to scattering), and therefore difficult to justify for a weight-limited, long duration mission such as MJU79.

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EDUCATION:

1958	B.S.	Physics, U. of New Hampshire
1959	M.S.	Physics, U. of New Hampshire
1965	Ph.D.	Physics, U. of New Hampshire

PREVIOUS POSITIONS:

6/59 - 9/62	Instructor, Physics, U. of N.H.
6/63 - 9/63	Res. Physicist, U. of N.H.
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PROFESSIONAL SOCIETY MEMBERSHIPS:
American Geophysical Union (Planetary Science)
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GSFC PROJECTS:
Principal Investigator for an experiment on Helios A and B
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PUBLICATIONS

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"The Interplanetary Acceleration of Energetic Nucleons", F. B. McDonald, B. J. Teegarden, J. H. Trainor, T. T. von Rosenvinge and W. R. Webber, submitted for publication, July 1975.

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	1939 - Ph.D.	State University of Iowa
PREVIOUS POSITIONS:	1939 - 1941	Research Fellow of Carnegie Institution of Washington, Nuclear Physics
	1941 - 1942	Physicist, Dept. of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D.C.
	1942	Physicist, Applied Physics Laboratory, Johns Hopkins Univ.
	1942 - 1946	Ordnance and Gunnery Officer and Combat Observer, U.S. Navy Lt. (j.g.) U.S.N.R. - 1942 Lt. Cdr. U.S.N.R. - 1946
	1946 - 1950	Physicist, Applied Physics Laboratory, Johns Hopkins Univ. Supervisor high-altitude research group and supervisor proximity fuze unit. Engaged in high altitude experiments in cosmic rays, atmospheric ozone, geomagnetic field, ultra-violet solar spectroscopy, high altitude photography of the earth. Pioneered in use of V-2 rockets for this work. Supervised development of Aerobee rocket and pioneered in its use for similar work.
	1951 - 1972	Professor of Physics and Head of Department of Physics (since 1959 Dept. of Physics and Astronomy), University of Iowa
SPECIAL PROFESSIONAL ACTIVITIES:	Leader, Scientific Expedition to Central Pacific on U.S.S. Norton Sound, 1949, for study of cosmic rays and earth's magnetic field, using Aerobee rockets. Leader, Scientific Expedition to Gulf of Alaska on U.S.S. Norton Sound, 1950, for study of cosmic rays, using Aerobee rockets. Leader, Scientific Expedition to Arctic on U.S.C.G.C. Eastwind, 1952, for study of cosmic rays with balloon-launched rockets.	

Leader, Scientific Expedition (I.G.Y.) to Arctic on U.S.S. Plymouth Rock, 1957, for study of cosmic rays, aurorae, and geomagnetic field with balloon-launched rockets and to Atlantic, Central Pacific, South Pacific, and Antarctic areas on U.S.S. Glacier, 1957, for same purposes.

Research Fellow, Guggenheim Memorial Foundation 1951, at Brookhaven National Laboratory.

Research Associate, Princeton University, Project Matterhorn, 1953-54, for early experimental work on controlled thermonuclear reactions.

Associate Editor, Physics of Fluids, 1958-62.

Associate Editor, Journal of Geophysical Research, 1959-1967.

Member, Editorial Board, Space Science Reviews, 1962-1974.

Lecturer, Enrico Fermi International Summer School, Varenna, Italy, 1962.

Lecturer, NATO Conference, Bergen, Norway, 1965.

PROFESSIONAL SOCIETY MEMBERSHIPS:

Fellow, American Physical Society
Fellow, American Geophysical Union
Member, Iowa Academy of Science
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Fellow, Institute of Electrical and Electronics Engineers
Fellow Member, American Astronautical Society
Member, American Astronomical Society
Member, Sigma Xi
Member, Gamma Alpha
Member, Cosmos Club
Fellow, American Rocket Society
Member, Royal Astronomical Society (U.K.)
Member, American Philosophical Society
Fellow, American Academy of Arts and Sciences

COMMITTEES:

Member, Rocket and Satellite Research Panel (formerly V-2 Rocket Panel, then Upper Atmosphere Rocket Research Panel) 1946 to date, Chairman 1947-1958, and member executive committee 1958 to date.

Member, Technical Panel on Earth Satellite Program (I.G.Y.) 1955-1958 and Chairman, Working Group on Internal Instrumentation 1956-1958.

Member, Technical Panel on Rocketry (I.G.Y.) 1955-1958.

Member, Technical Panel on Cosmic Rays (I.G.Y.) 1956-1958.

Member, Technical Panel on Aurora and Airglow (I.G.Y.) 1957-1958.

Member, Subcommittee on Upper Atmosphere, National Advisory Committee on Aeronautics 1948-1952.

Member, Advisory Committee on Nuclear Physics, Office of Naval Research, 1957-1960.

Member, Advisory Committee on Physics, National Science Foundation, 1957-1960.

Consultant, President's Science Advisory Committee, 1962-1963.

Member, Space Science Board of the National Academy of Sciences, 1958-1970.

Member, Particles and Fields Subcommittee of Space Science and Applications Steering Committee, NASA, 1959-1963; 1966-1969.

Member, Panel on Science and Technology of the Committee on Science and Astronautics of the U.S. House of Representatives, 1959-1972.

President, Planetary Sciences Section, Am. Geophysical Union, 1964-1968.

Chairman, Iowa's International Cooperation Year Committee on Science and Advanced Technology, 1965.

Member, Ad Hoc Science Advisory Committee, NASA, 1967.

Chairman, Ad Hoc Panel on Small Planetary Probes, Space Science Board, National Academy of Sciences, 1966.

Member, Lunar and Planetary Missions Boards, NASA (also Chairman, Jupiter Panel), 1967-1971.

Governor's Science Advisory Committee, 1967-1969.

Director-at-Large, Association of Universities for Research in Astronomy (AURA), Inc.; Chairman of Space Subcommittee, Scientific Committee, March 1968-March 1971.

Member, U.S. Committee for the Global Atmospheric Research Program (USC-GARP), 1968 through June 30, 1970.

Member, AGU Selections Committee for John A. Fleming Award, 1968.

Member, CALTECH Board of Visitors, 1968.

Member, Science Advisory Group/Outer Solar System Missions, JPL/NASA 1970-1972. Consultant: 1 June 1971-1 June 1972).

Chairman, Outer Planets Science Working Group (OPSWG), Sept. 1972 ...

Chairman, Outer Planets Science Advisory Committee (OPSWG), 1973.

Chairman, Mariner Jupiter Uranus/Science Advisory Committee, Dec. 1973-Oct. 1974.

Co-Chairman, NASA Pioneer Jupiter Orbiter Mission, Definition Group, May-Dec. 1974.

President, Solar and Planetary Section American Geophysical Union 1975 ...

Member, Committee on Planetary and Lunar Exploration, Space Science Board, National Academy of Sciences, 1975 ...

Member, Board of Governors of the National Space Institute, 1975 ...

Member, Arecibo Advisory Board, 1975 ...

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EXPLORER 14
EXPLORER 15
INJUN 3
OGO 1
EXPLORER 25 (INJUN 4)
MARINER 4
OGO 2
EXPLORER 33 (AIMP-D)
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HONORS, etc.:

1949	C.N. Hickman medal of American Rocket Society for development of Aerobee.
1949	Physics award of Washington Academy of Science.
1951	Doctor of Science degree, Iowa Wesleyan College.
1957	Doctor of Science degree, Grinnell College.
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1960	Doctor of Science degree, Univ. of Dubuque.
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1963	Doctor of Science degree, Illinois College.
1966	Doctor of Science degree, Boston College
1966	Doctor of Science degree, Butler University.
1967	Doctor of Science degree, Southampton College.
1969	Doctor of Science degree, Augustana College.

1958	Space Flight Award, Am. Astronautical Society.
1959	Distinguished Civilian Service medal (US Army).
1960	Louis W. Hill 1959 Space Transportation Award.
1961	First Iowa Award in Science.
1961	First Annual Research Award, Am.Rocket Society.
1961	Elliot Cresson medal, Franklin Institute.
1962	David and Florence Guggenheim Int. Astronautics Award.
1963	John A. Fleming Award, Am. Geophysical Union.
1963	Golden Omega Award, Electrical Insulation Conf.
1964	John A. Fleming Award, Am. Geophysical Union (Second Recipient).
1964	Commander of the Order du Merite pour la Recherche et L'Invention.
1964	Iowa Broadcasters Association Award.
1972	Carver Distinguished Professor, Univ. of Iowa.
1974	NASA Medal for Exceptional Scientific Achievement.
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"Catalog of Solar X-Rays Solar Geophysical Data", J. A. Van Allen, Environmental Data Service, U.S. Department of Commerce, IER-FB-275 to IER- 3-299, Part II, SGD-300 to SGD-338, Part II, July 1966 - October 1972.

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EDUCATION

1964	License es Sciences, University of Paris, France, Physics
1968	D.E.A., University of Paris, France, Geophysics
1970	Doctorat in Geophysics, University of Paris, France

PREVIOUS POSITIONS:

1970 - 1971	Post doctoral ESRO Fellowship NASA/Goddard Space Flight Center
1968 - 1970	Research Assistant, Laboratoire de Physique Cosmique, Verrieres Buisson, France
1963 - 1968	Research Assistant, Laboratoire de Physique generale Dr. Morand, Faculte des Sciences, Paris, France

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RESEARCH AREA EXPERIENCE:	Research on the astrophysical aspects of cosmic radiation. Principal Investigator on NASA Grant NGR 05-002-160 supporting space research at Caltech. Co-investigator on cosmic ray experiments on NASA's OGO-6, IMP 7 & 8, HEAO A, and Principal Investigator on MJS77.	
EDUCATION:	1957 - S.M.	University of Chicago
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PREVIOUS POSITIONS:	1953 - 1961	Research Assistant Enrico Fermi Institute for Nuclear Studies, University of Chicago
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PROFESSIONAL SOCIETY MEMBERSHIPS:	American Physical Society (Fellow) American Geophysical Union American Association of Physics Teachers American Association for the Advancement of Science	

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"The Quiet Time Flux of 0.16 - 1.6 MeV Cosmic Ray Positrons", R. E. Vogt, R. A. Mewaldt and E. C. Stone, 14th Int. Cosmic Ray Conf., Munich, to be published 1975.

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"Enrichment of Heavy Nuclei in ^{3}He Rich Flares", R. E. Vogt, G. J. Hurford, R. A. Mewaldt and E. C. Stone, Ap. J., in press, 1975.

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RESEARCH AREA EXPERIENCE:	Design and execution of balloon and satellite experiments to study solar and galactic cosmic rays.	
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"Measurements of the Energy Spectrum of Nuclei with $Z > 3$ in the Primary Radiation Using a Balloon-Borne Cerenkov, Scintillation Counter", W. R. Webber, J. F. Ormes and T. von Rosenvinge, Proc. of 9th Int. Conf. on Cosmic Rays, London, 1965.

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"The Interplanetary Acceleration of Energetic Nucleons", F. B. McDonald, B. J. Teegarden, J. H. Trainor, T. T. von Rosenvinge and W. R. Webber, submitted for publication, July 1975.

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1957 - 1958	Research Fellow, Imperial College
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1959 - 1961	NSF Postdoctoral Fellow Imperial College
1961 - 1964	Asst. Prof., Univ. of Minnesota
1964 - 1967	Assoc.Prof., Univ. of Minnesota
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1971	Visiting Prof., Danish Space Research Institute-Copenhagen
1968 - 1972	Dir. Space Science Center University of New Hampshire
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RESEARCH AREA EXPERIENCE:

Cosmic Ray Charge Composition and Nucleosynthesis in Stars
Cosmic Ray Electrons and their Motion and the Galaxy and Universe
X-Ray Astronomy
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Solar Modulation of Cosmic Rays and the Propagation of Solar Cosmic Rays
Interplanetary Charged Particles
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PROJECTS: Principal Investigator on Cosmic Ray Experiments on the OGO C & D Satellites, Pioneer 8 & 9 space probes, and co-investigator on Pioneer 10 & 11 Jupiter probes. Co-investigator on Cosmic Ray Experiment to be flown on MJS (Mariner Jupiter-Saturn) deep space probe

PROFESSIONAL SOCIETY MEMBERSHIPS:

American Physical Society
American Astronomical Society
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SPECIAL PROFESSIONAL ACTIVITIES:

Member, NASA subcommittee on fields and particles, 1964-67.
Associate Editor, JGR, 1964-68, 1971-73.
Invited participant in NAS Woods Hole Study for Scientific Uses of the Moon, 1966.
NAS Ground Based Techniques of Space Research, Aspen, 1969.
Seminar on Interplanetary Physics given at Latin American School of Physics, Tucuman, 1964.
Seminar on Cosmic Ray Modulation given at the Solar Terrestrial Physics Symposium in Lenningrad, 1969.
Seminar on Galactic Cosmic Rays given at Inter-American Symposium on Cosmic Rays and Galactic Objects, Sao Paulo, 1972.
Past consultant at Boeing Company and North American Aviation

"Determination of the Intensities of Low-Z Components of the Primary Cosmic Radiation at $\lambda=41°$ Using a Cerenkov Detector", W. R. Webber and F. B. McDonald, Phys. Rev. 100, 1460, 1955.

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