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RESEARCH IN COSMIC AND GAMMA RAY ASTROPHYSICS

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INTRODUCTION

Research in cosmic ray and gamma ray astrophysics at the Space Radiation Laboratory (SRL) of the California Institute of Technology was supported by NASA grant NGR-05-002-160 during the period October 1, 1969 to March 31, 1990 after which this support was shifted to NASA Grant NAGW-1919. We submit here the Final Report for grant NGR-05-002-160, summarizing two decades of activities.

The primary activities supported by this grant have been the development of new instrumentation and techniques for future space flight. In many cases, these instrumentation developments have been tested in balloon flight instruments designed to conduct new investigations in cosmic ray and gamma ray astrophysics. The results of these investigations are briefly summarized in Section 2, for details the reader is referred to the Bibliography. Section 3 summarizes laboratory activities supported by this grant.

In addition SRL has participated in a large number of activities involving experiments in space that have indirectly benefited through the support of this grant (see Section 4).

Over the course of the last two decades more than twenty Ph.D.'s have completed their thesis research in SRL and an approximately equal number of post-doctural fellows have received training. These and other educational activities supported by this grant are documented in Section 5. In Section 6, we document some of the many other community service activities carried on by SRL personnel. Finally, Section 7 contains a complete bibliography of papers and Ph.D. theses completed over the course of this grant. It is these papers that contain actual record of the broad range of activities that are summarized briefly in this Final Report.

2.0 Activities in support of Experiments under Development for Future Space Flight

2.1 A Quantitative Investigation of the Solar Modulation of Cosmic-Ray Protons and Helium Nuclei

The differential energy spectra of cosmic-ray protons and He nuclei have been measured at energies up to 315 MeV/nucleon using balloon-and satellite-borne instruments, including spectra for solar quiet times for the years 1966 through 1970. The data analysis has been verified by extensive accelerator calibrations of the detector systems and by calculations and measurements of the production of secondary protons in the atmosphere.

The spectra of protons and He nuclei in this energy range are dominated by the solar modulation of the local interstellar spectra. The transport equation governing this process includes as parameters the solar-wind velocity, V, and a diffusion coefficient, $\kappa(r,R)$, which is assumed to be a scalar function of heliocentric radius, r, and magnetic rigidity, R. The interstellar spectra, j_D, enter as boundary conditions on the solutions to the transport equation. Solutions to the transport equation have been calculated for a broad range of assumed values for $\kappa(r,R)$ and j_D and have been compared with the measured spectra.

It is found that the solutions may be characterized in terms of a dimensionless parameter,

$$\psi(r,R) = \int_r^\infty \frac{V\,dr'}{\kappa(r',R)}.$$

The amount of modulation is roughly proportional to ψ. At high energies or far from the Sun, where the modulation is weak, the solution is determined primarily by the value of ψ (and the interstellar spectrum) and is not sensitive to the radial dependence of the diffusion coefficient. At low energies and for small r, where the effects of adiabatic deceleration are found to be large, the spectra are largely determined by the radial dependence of the diffusion coefficient and are not very sensitive to the magnitude of ψ or to the interstellar spectra. This lack of sensitivity to j_D implies that the shape of the spectra at Earth cannot be used to determine the interstellar intensities at low energies.

Values of ψ determined from electron data were used to calculate the spectra of protons and He nuclei near Earth. Interstellar spectra of the form $j_D \alpha (W - 0.25m)^{-2.65}$ for both protons and He nuclei were found to yield the best fits to the measured spectra for these values of ψ, where W is the total energy and m is the rest energy. A simple model for the diffusion coefficient was used in which the radial and rigidity dependence are separable and κ is independent of radius inside a modulation region which has a boundary at a distance D. Good agreement was found between the measured and calculated spectra for the years 1965 through 1968, using typical boundary distances of 2.7 and 6.1 A.U. Figure 1 shows examples of the fits to the data. The proton spectra observed in 1969 and 1970 were flatter than in previous years. This flattening could be explained in part by an increase in D, but also seemed to require that a noticeable fraction of the observed protons at energies as high at 50 to 100 MeV be attributed to quiet-time solar emission. The turn-up in the spectra at low energies observed in all years was also attributed to solar emission. The diffusion coefficient used to fit the 1965 spectra is in reasonable agreement with that determined from the power spectra of the interplanetary magnetic field. We find a factor of roughly 3 increase in ψ from 1965 to 1970, corresponding to the roughly order of magnitude decrease in the proton intensity at 250 MeV. The change in ψ might be attributed to a decrease in the diffusion coefficient, or, if the diffusion coefficient is essentially unchanged over that period, might be attributed to an increase in the boundary distance, D.

2.2 A Study of Cosmic-Ray Positron and Electron Spectra in Interplanetary and Interstellar Space and The Solar Modulation of Cosmic Rays

We have measured the differential energy spectra of cosmic-ray positrons and negatrons with energies between ~11 and 1500 MeV during the period 1968-1971 using a balloon-borne magnetic spectrometer. These measurements fill a gap in the previously existing data and permit us to determine, within quantitative limits, the interstellar spectra of cosmic-ray positrons and electrons ($e^+ + e^-$). Knowledge of these spectra provides a crucial tool for studies of the distribution and density of matter and magnetic fields in the interstellar medium and the origin and dynamics of energetic particles contained in the fields.

From a study of the near-Earth electron spectra and their relationship to the interstellar spectrum derived from the galactic non-thermal-radio-background emission, and from a study of the near-Earth positron spectra and their relationship to the interstellar positron spectrum calculated from collisions of cosmic-ray nuclei with the interstellar matter, we have found that the differential energy spectrum of interstellar electrons may be represented as a power-law, $j \alpha T^{-1.8}$ for 100 MeV $\leq T \leq$ 2 GeV, but must flatten considerably at lower energies. From the measured electron charge composition, which we find to be little affected by solar modulation, we have concluded that the majority of cosmic-ray electrons with energies above ~10 MeV are not the result of nuclear collisions in the galaxy but presumably originate in "primary" sources. Figure 2 shows our estimate of the interstellar electron spectrum.

In the energy range of our measurements the near-Earth intensities of cosmic-ray positrons and electrons, as well as the intensity of cosmic-ray nuclei, are significantly lower than their interstellar intensities because the particles are scattered by magnetic irregularities imbedded in the outward-flowing plasma of the solar wind. Long-term changes in the scattering properties of the interplanetary medium, i.e. in the cosmic-ray diffusion coefficient, κ, are responsible for the observed long-term variations in the near-Earth cosmic-ray intensities which are as large as a factor of 10 from "solar minimum" to "solar maximum". We have used the cosmic-ray positron and electron spectra as tools to study the solar modulation mechanism. By using numerical solutions of the cosmic-ray transport equation to relate the near-Earth electron spectra to the interstellar electron spectrum, we have found that the magnetic rigidity dependence of the interplanetary cosmic-ray diffusion coefficient at rigidities form ~100 MV to ~10 GV may be represented as $\kappa \alpha$

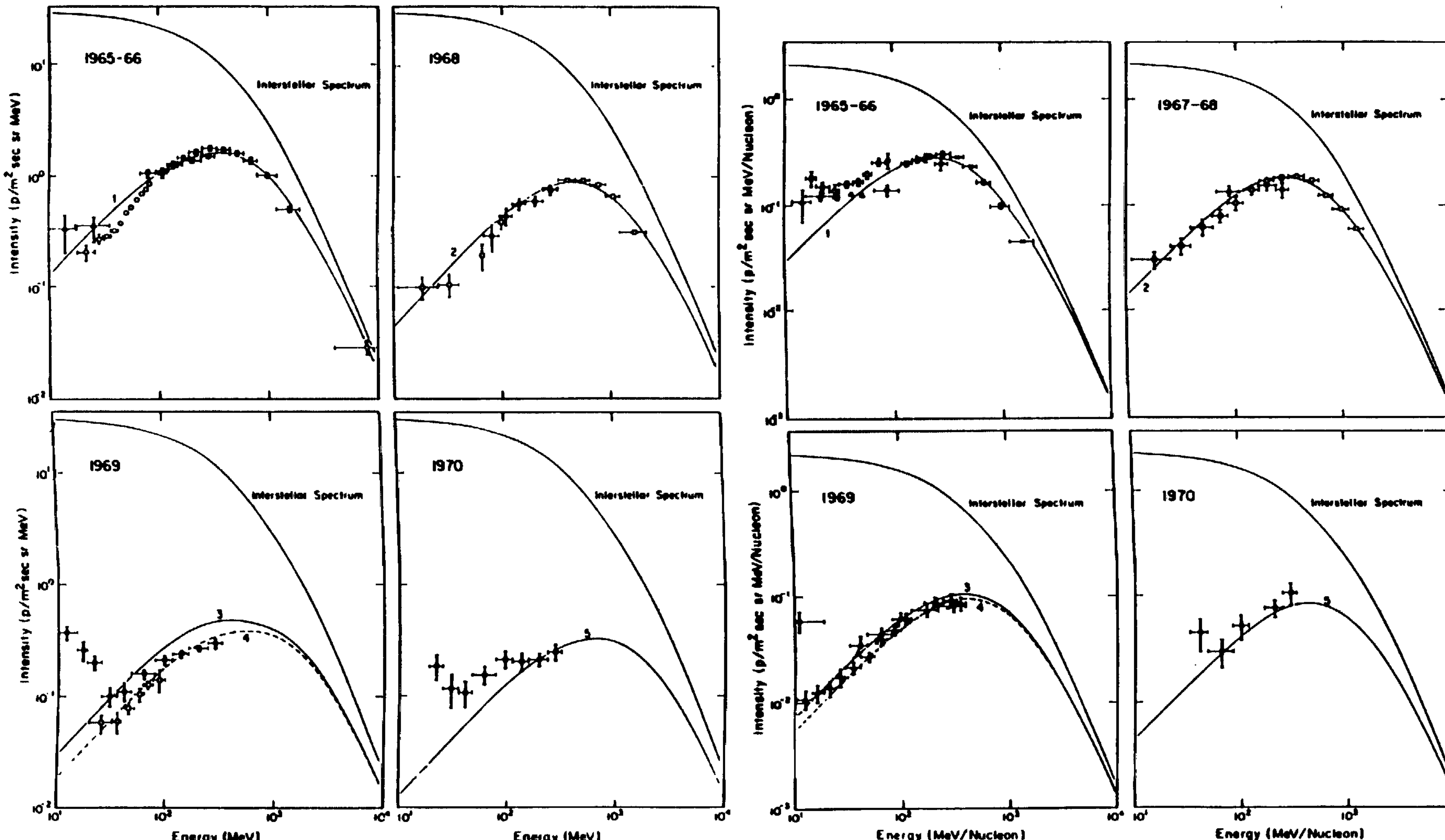


Figure 1: Calculated and measured spectra of cosmic-ray protons (left) and He nuclei (right) at 1 AU for epoches marked.

R^b with b increasing from 0 to ~1-2 with increasing rigidity. However, from a comparison of the near-Earth and interstellar positron spectra we find that below ~60 MV the diffusion coefficient must increase with decreasing rigidity.

The magnitude of the diffusion coefficient at 1 AU derived from the electron and positron modulation studies depends on the assumed radial dependence of κ. In order to place limits on this radial dependence and to make estimates of the size of the solar modulation region, we have also evaluated diffusion coefficients from measurements of the power spectrum of the interplanetary magnetic field near 1 AU. Assuming κ (r) α r^n, we have found that $n \leq 1.1$ in order that the calculated modulation beyond 1 AU agrees with the observed modulation. For κ independent of radius, we obtained consistency between the diffusion coefficients derived by the two methods for boundary distances of the solar modulation region in the range of 6-25 AU.

These diffusion coefficients derived from the electron modulation study must also apply to the cosmic-ray nuclei. As a consistency check, we have used the electron diffusion coefficients to calculate solutions of the transport equation for cosmic-ray protons and He nuclei for four different time periods from 1965 to 1970. Assuming a particular, time-independent form for the interstellar spectra of these particles, we have derived spectra at 1 AU which are consistent with the observations over the full range of intensity variations observed during this solar half cycle.

2.3 An Investigation of Techniques for the Measurement and Interpretation of Cosmic Ray Isotopic Abundances

An instrument, the Caltech Proportional Counter Cesnum Iodide Spectrometer Telescope (PCIST), has been developed to measure isotopic abundances of cosmic ray nuclei in the charge range $3 \leq Z \leq 28$ and the energy range between 30 and 800 MeV/nuc by employing an energy loss - residual energy technique. Measurements of particle trajectories and energy losses are made using a multiwire proportional counter hodoscope and a stack of CsI(Tl) crystal scintillators, respectively. A detailed analysis has been made of the mass resolution capabilities of this instrument.

Landau fluctuations set a fundamental limit on the attainable mass resolution, which for this instrument ranges between ~.07 amu for for $Z = 3$ and ~.2 amu for Z ~26. Contributions to the mass resolution due to uncertainties in measuring the path-length and energy losses of the detected particles are shown to degrade the overall mass resolution to between ~.1 amu ($Z = 3$) and ~.3 amu ($Z = 26$).

A formalism, based on the leaky box model of cosmic ray propagation, is developed for obtaining isotopic abundance ratios at the cosmic ray sources from abundances measured in local interstellar space for elements having three of more stable isotopes, one of which is believed to be absent at the cosmic ray sources. This purely secondary isotope is used as a tracer of secondary production during propagation. This technique is illustrated for the isotopes of the elements O, Ne, S, Ar and Ca.

The uncertainties in the derived source ratios due to errors in fragmentation and total inelastic cross sections, in observed spectral shapes, and in measured abundances are evaluated. It is shown that the dominant sources of uncertainty are uncorrelated errors in the fragmentation cross sections and statistical uncertainties in measuring local interstellar abundances.

The results are applied to estimate the extent to which uncertainties must be reduced in order to distinguish between cosmic ray production in a solar-like environment and in various environments with greater neutron enrichments.

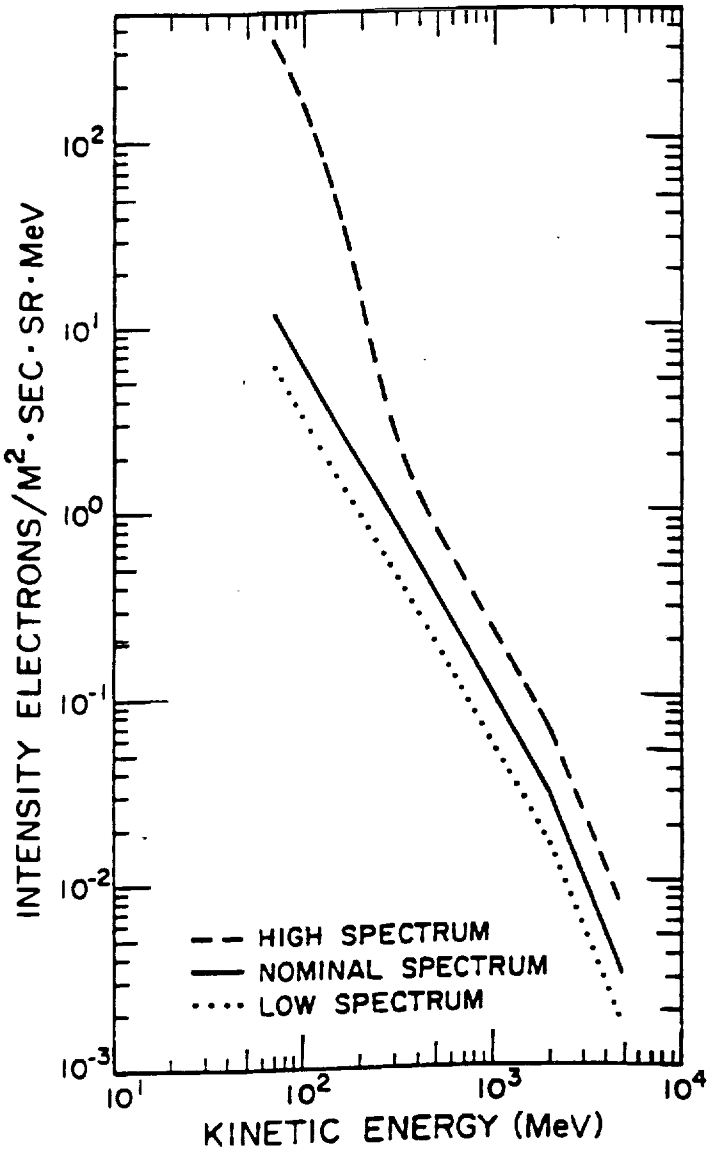


Figure 2: Interstellar electron spectra derived from the non-thermal-radio-background data.

2.4 A Balloon Measurement of the Isotopic Composition of Galactic Cosmic Ray Boron, Carbon, and Nitrogen

The Caltech Proportional Counter Isotope Spectrometer Telescope (PCIST) has been used to measure the isotopic composition of galactic cosmic ray boron, carbon, and nitrogen with energies near ~300 MeV/nucleon. The data were obtained in a balloon flight of the instrument from Yorkton, Saskatchewan, Canada on 8/30/78 at an atmospheric depth of ~5 g/cm^2.

PCIST determines isotopic mass by comparing the energy loss in the individual members of a stack of cesium-iodide scintillators within which the cosmic ray nuclei are brought to rest. A cross section of the sensor system is shown in Figure 3. The trajectory of the incident particle is determined by the 8 multi-wire proportional counters and the energy loss of the particle is determined by the scintillation light output (L) from each of the CsI(T1) disks as the particle slows down and comes to rest within the scintillator stack.

The light output L is related in a non-linear way to the particle energy E from which the mass M of the stopping particle can be determined. The dependence of L on E can be determined from flight data for the elements B, C and O and then used to derive the isotopic distribution for each individual element. Figure 4 shows the measured mass distributions for cosmic ray boron, carbon, and nitrogen. Each plot has two associated mass scales, depending on which isotope was used in the E vs L conversion. Note that for boron, for example, the lower mass peak occurs at 10 amu on the ^{10}B scale and the higher mass peak at 11 amu on the ^{11}B mass scale, confirming the validity of the E/L conversion for different isotopes. The observed mass resolution in Figure 4 ranges from 0.32 amu at boron to 0.50 amu at nitrogen, consistent with the expected resolution.

Isotopic ratios were determined from the data in Figure 4 using the maximum likelihood method. The results are summarized in Table 1, where the abundances have been corrected to the top of the atmosphere.

Table 1
Measured Isotope Abundances
- Top of Atmosphere -

Element	Isotope	Energy Interval (MeV/nuc)	Isotopic Composition
Boron	^{10}B	264-300	$^{10}B/B = 0.33^{+.17}_{-.11}$
	^{11}B	249-282	
Carbon	^{12}C	293-335	$^{13}C/C = 0.06^{+.13}_{-.01}$
	^{13}C	279-318	
Nitrogen	^{14}N	320-367	$^{15}N/N = 0.42^{+.19}_{-.17}$
	^{15}N	306-352	

In Figure 5 the measured isotope abundances are compared with selected other observations, and with the results of cosmic ray propagation and solar modulation calculations. The dashed curves in Figure 5 show the calculated interstellar ratios, while the solid curves include the effects of solar modulation characterized by a mean energy loss $\Phi = 300$ MeV/nuc.

For boron, the ensemble of the measurements is in reasonable agreement with the predictions of the model. Since cosmic ray boron is thought to be entirely of secondary origin, this agreement provides confirming evidence that the propagation model is reasonable and the relevant cross sections are adequately described by the semi-empirical formulae.

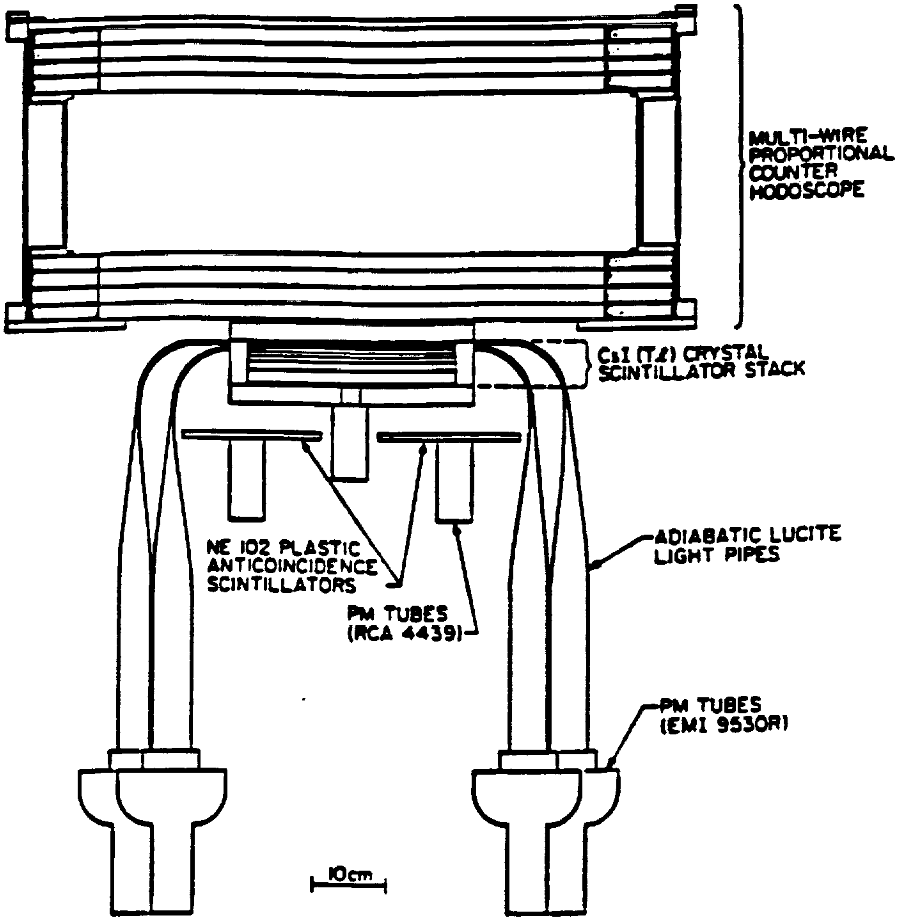


Figure 3

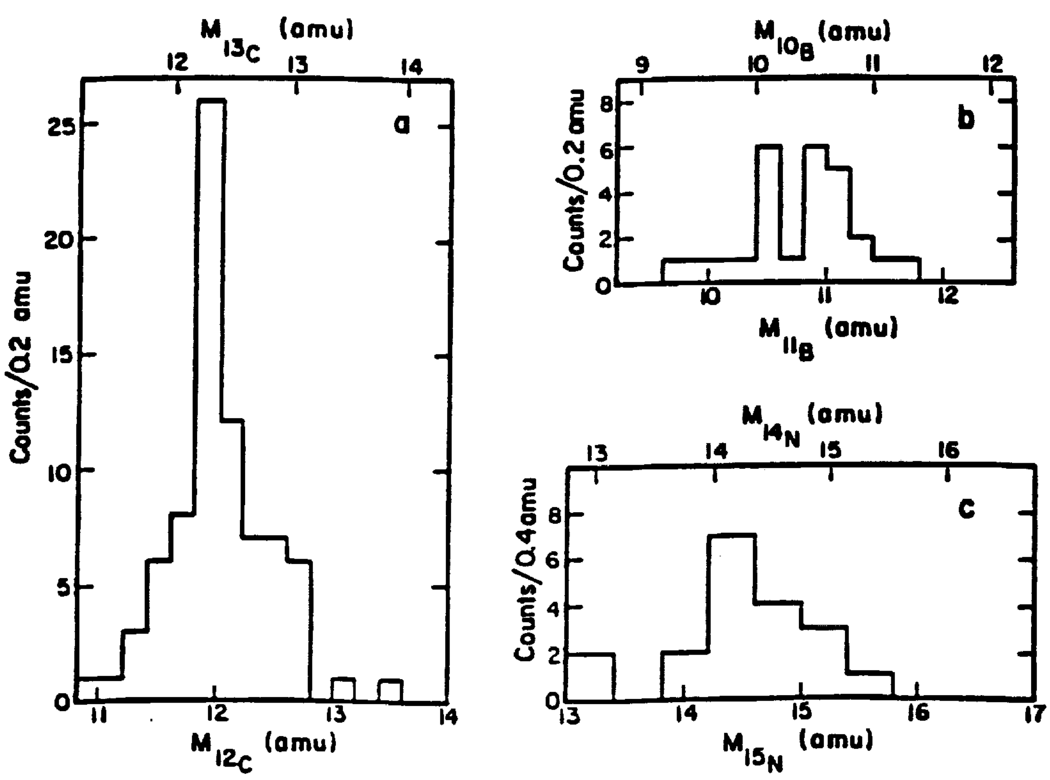
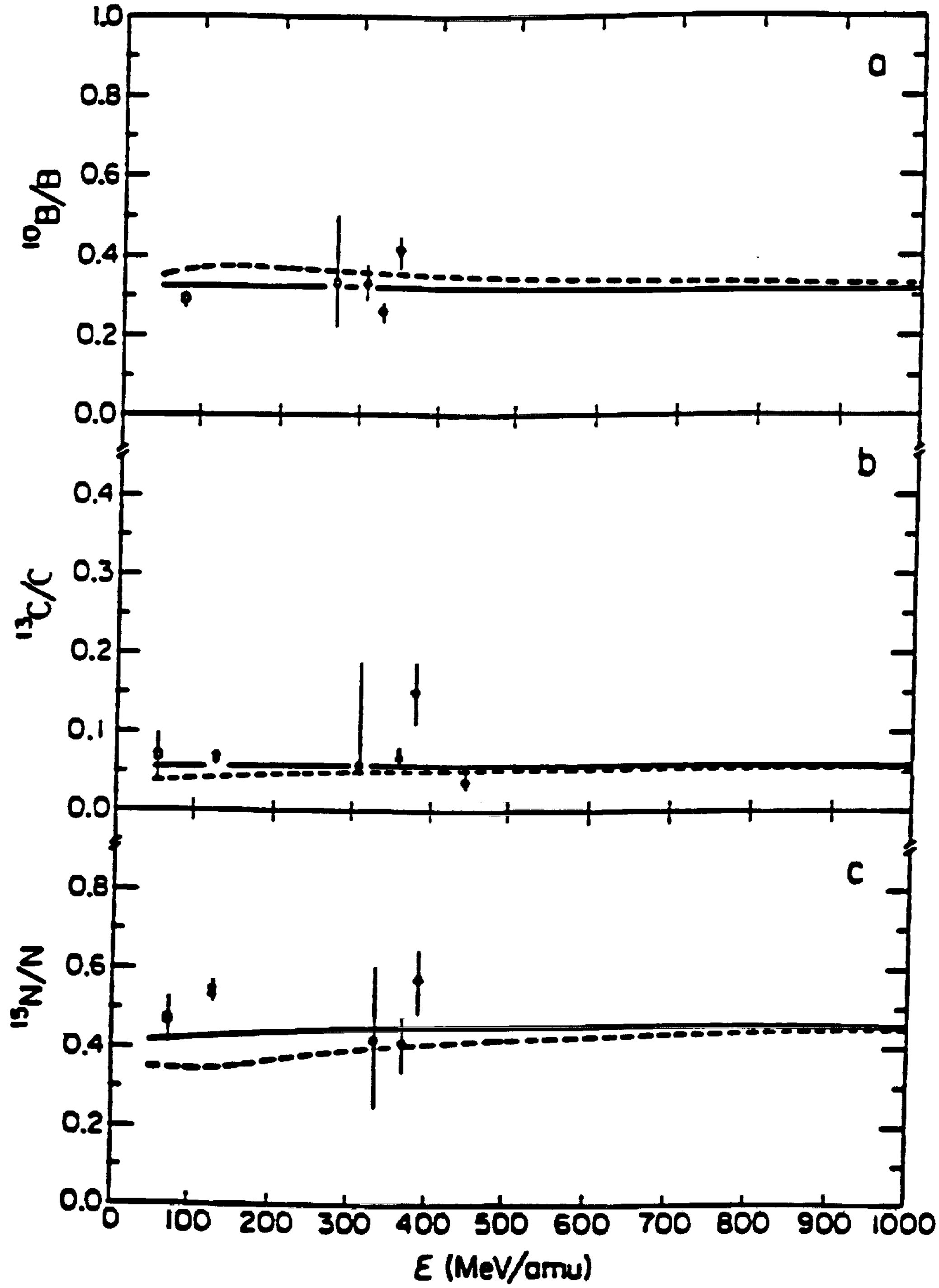


Figure 4



1.0
0.8
0.6
0.4
0.2
0.0
$^{10}B/B$
a
0.4
0.3
0.2
0.1
0.0
$^{13}C/C$
b
0.8
0.6
0.4
0.2
0.0
$^{15}N/N$
c
0
100
200
300
400
500
600
700
800
900
1000
E (MeV/amu)

Figure 5

For carbon it can be seen that the solar like composition assumed for the calculation is consistent with the majority of the observations. The measurements rule out a hot ($T > 10^8$ °K) equilibrium CNO bi-cycle as a major contributor to cosmic ray carbon, as this would produce a $^{13}C/C$ ratio approaching 0.2.

For nitrogen, there is some indication that more ^{15}N is observed than is predicted by the model. Although this might be taken as indication that ^{15}N is enhanced in the cosmic ray source over its solar abundance ($^{15}N/N = 0.004$), Gusik has suggested that the semi-empirical cross sections for nitrogen production may be in error. Taking his revised cross section into account, and considering the uncertainties in the assumed interstellar pathlength and solar modulation level, we conclude that the ^{15}N abundance at the cosmic ray source is marginally consistent with its solar system value.

In summary, the observed abundances of B, C, and N isotopes are consistent with a cosmic ray source of solar system composition, and with standard propagation and solar modulation models. However, the observations do not as yet rule out the possibility that the neutron rich isotopes of C and N are enhanced by a factor of ~2 is cosmic rays, as in recent observations of cosmic ray Ne and Mg neutron-rich isotopes.

2.5 A Balloon Measurement of the Antiproton (P) Flux in the Cosmic Rays

There is interest in cosmic-ray antiproton fluxes, not only because of the possible exotic sources of antiprotons, but also because this particle is the only secondary expected to come mostly from proton interactions, but without spectrum-changing interactions (as with positrons) with photons. This experiment, which was performed jointly between SRL and the Space Sciences Laboratory at Berkeley, measured antiprotons at a few hundred MeV, where the secondary spectrum is expected, even with the effects of solar modulation included, to be strongly suppressed due to production kinematics.

Figure 6 shows a schematic diagram of the instrument. The apparatus selects P events from the larger background of normal matter cosmic rays by combining a selective trigger with a detailed spark-chamber visualization. The top scintillators (S_1, S_2, and S_3) and the Cerenkov counter "C" select events typically have an incident velocity < 300 MeV/nucleon. The trigger requirement is S_1 through S_4 in coincidence, and C in anticoincidence. Once the trigger criteria are satisfied, the spark chambers are operated, giving a photographic record of the detailed event topology. The selective trigger provides an approximately 1000-fold rejection against normal cosmic-ray events, with an efficiency of about 10% for recording P annihilations. An oscilloscope record of the scintillator and Cerenkov counter responses (pulse height and timing) also appears on the film.

The experiment was flown from the The Pas, Canada, on 18 June 1980, at an average residual atmospheric depth of 11 g/cm^2. About 20,000 events were recorded.

About 1500 events were found by scanners to satisfy initial selection criteria: an incident track which connects to three or more straight or kinked prongs in the lead-plate chamber. When we examined these events, most proved to have either more than one energetic particle present, or some other topological uncertainty which the scanners felt deserved further analysis. However, 64 events were found to satisfy all the topological requirements. After further consistency checks fourteen antiproton candidates remained. Numerous crosschecks were carried out to be sure that no identifiable background process could be responsible for these P events.

Figures 7 and 8 present the measured flux and P/P ratio, together with other P measurements and calculations of expected fluxes if the P's are entirely secondary. The data do not show the expected drop in P flux at low energy; instead the P/P ratio could well be flat. Moreover, the integral flux of P's is substantially larger than that predicted by the standard galactic propagation models derived from studies of nuclei with $Z \geq 3$. This unexpected result suggests a

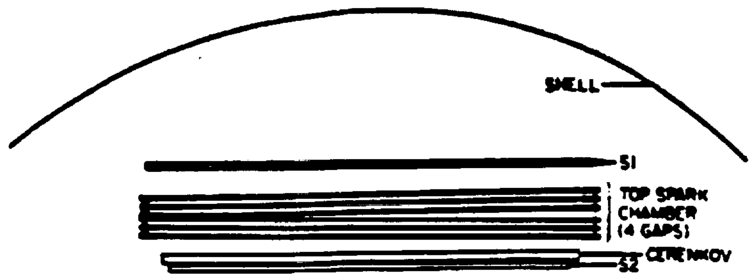
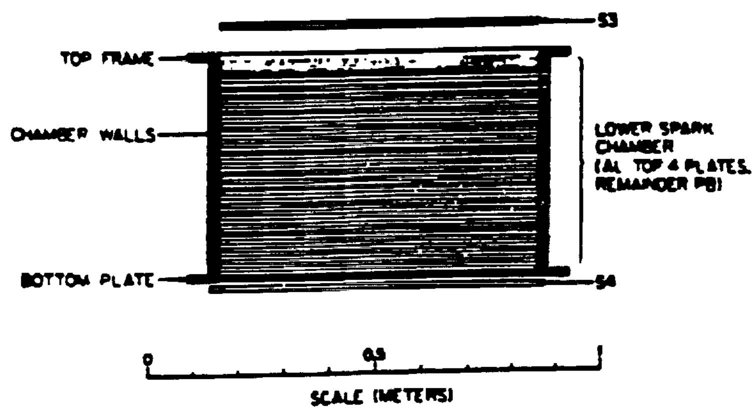


Figure 6



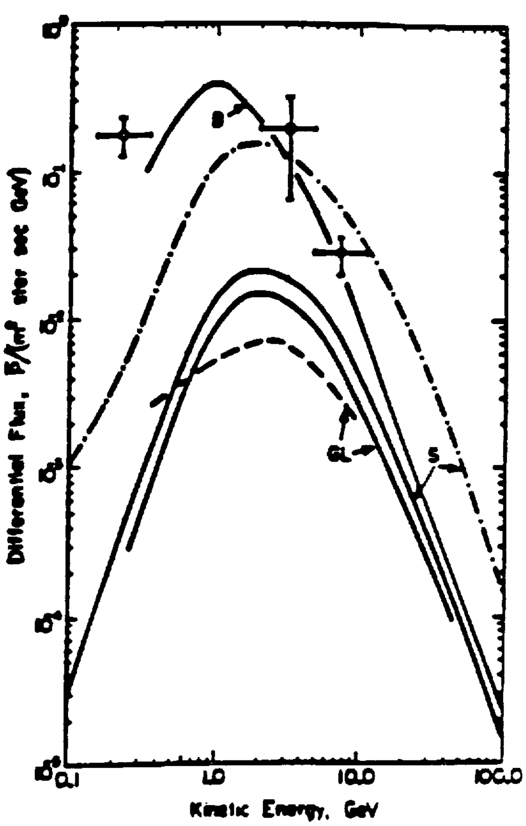


Figure 7

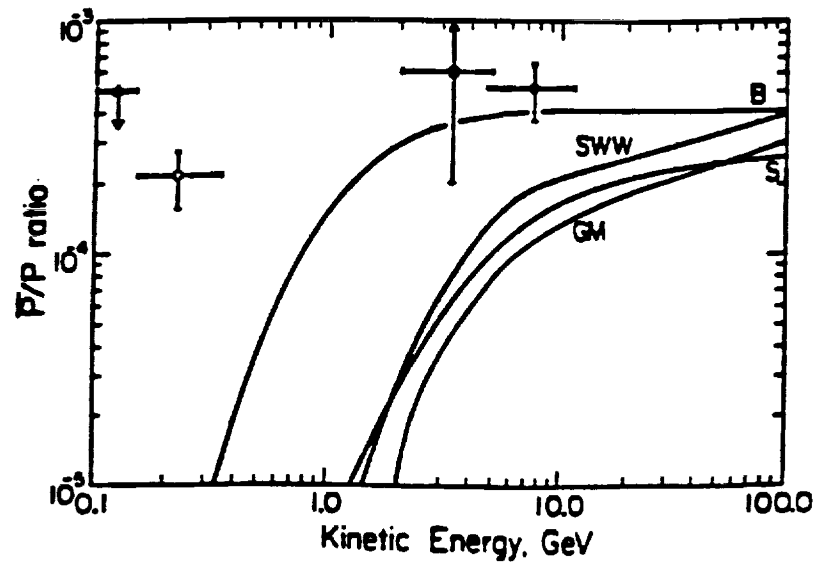


Figure 8

substantially different history for cosmic-ray protons compared with that for the medium or heavy elements, from which the parameters of the standard models are derived.

Postscript: During the late 1980's two new measurements of low energy antiprotons were performed by other groups which indicated substantially lower P/P ratios than were found in this experiment. As a result, the pioneering P measurement provided by this experiment is presently best regarded as an upper limit.

2.6 Gamma Ray Imaging Payload (GRIP)

The GRIP instrument is a balloon-borne imaging γ-ray telescope for galactic and extragalactic astronomy observations. The telescope employs a rotating lead coded-aperture mask and a large-area shielded NaI(Tl) scintillation camera to achieve good flux sensitivity over the energy range from 30 keV to 5 MeV and an imaging capability of 1070 0.6 degree pixels over a 20 degree field of view.

The primary detector is a position-sensitive NaI(Tl) scintillator viewed by 19 photomultiplier tubes (PMTs) which are individually pulse-height analyzed. Background in the primary detector is reduced by an active anti-coincidence shield. The side of the shield consists of 12 plastic scintillator modules which form a cylinder ~16 cm thick. Each module is viewed by a single 5" PMT. The lower shield section is identical to the primary camera plate.

The coded aperture is located 2.5 meters from the detector and is composed of 2000 cells of which half are open and half contain a lead hexagon 2 cm thick and 2.5 cm flat to flat. The pattern of open and filled cells forms a hexagonal uniformly redundant array that is optimal for coded aperture imaging.

During an observation the mask is continuously rotated to impose a time modulation of the γ-ray signal at each location on the detector. Due to the antisymmetry of the coded-aperture pattern under 60 degree rotation (open and closed cell interchange for all but the central cell) the γ-ray signal at each detector position is modulated with a 50% duty cycle. This feature allows a complete background subtraction to be performed for each position on the detector, once every 20 seconds. In addition, the continuous rotation permits extension of the field of view to 20 degrees, increasing the number of pixels imaged by about a factor of ten.

The telescope is mounted on an elevation/azimuth pointing platform which utilizes active magnetometer feedback. Two magnetometers provide aspect information permitting post-flight correction for pointing inaccuracies. The telescope pointing system is under microprocessor control, allowing steering by ground command or the execution of a pre-programmed flight plan. Data are recorded on-board and can also be telemetered to the ground for real-time analysis and redundant recording. The on-board recording system was developed for high capacity (25 Gbyte) and bandwidth (1.4 Mbit/s) using commercial VCRs and audio digitizers.

The GRIP instrument has had five flights during the period covered by this report. One of the primary objectives in these flights was the observation of SN 1987A in hard X-rays and γ-rays. Among the key features of the measurements were the detection and measurement of scattered gamma-ray continuum above 500 keV, detection of the 847 keV line from the supernova, and imaging observations of the supernova at energies above 50 keV. The measurement of continuum at energies above a few hundred keV is important for determination of line-to-continuum ratios which can be used to derive the opacity of the supernova remnant to MeV γ-ray emission, while imaging observations of the supernova are important to place limits on the flux contribution of other hard X-ray and γ-ray sources, in particular LMC X-1.

In addition to data from SN 1987A, observations were also made of the galactic center region. A strong source of emission was detected within 1° of the galactic center. Surprisingly, the emission does not come from the nucleus itself, but rather comes from ~0.7° away. We have tentatively identified the source as the Einstein source, 1E1740.7-2942. Although the observed

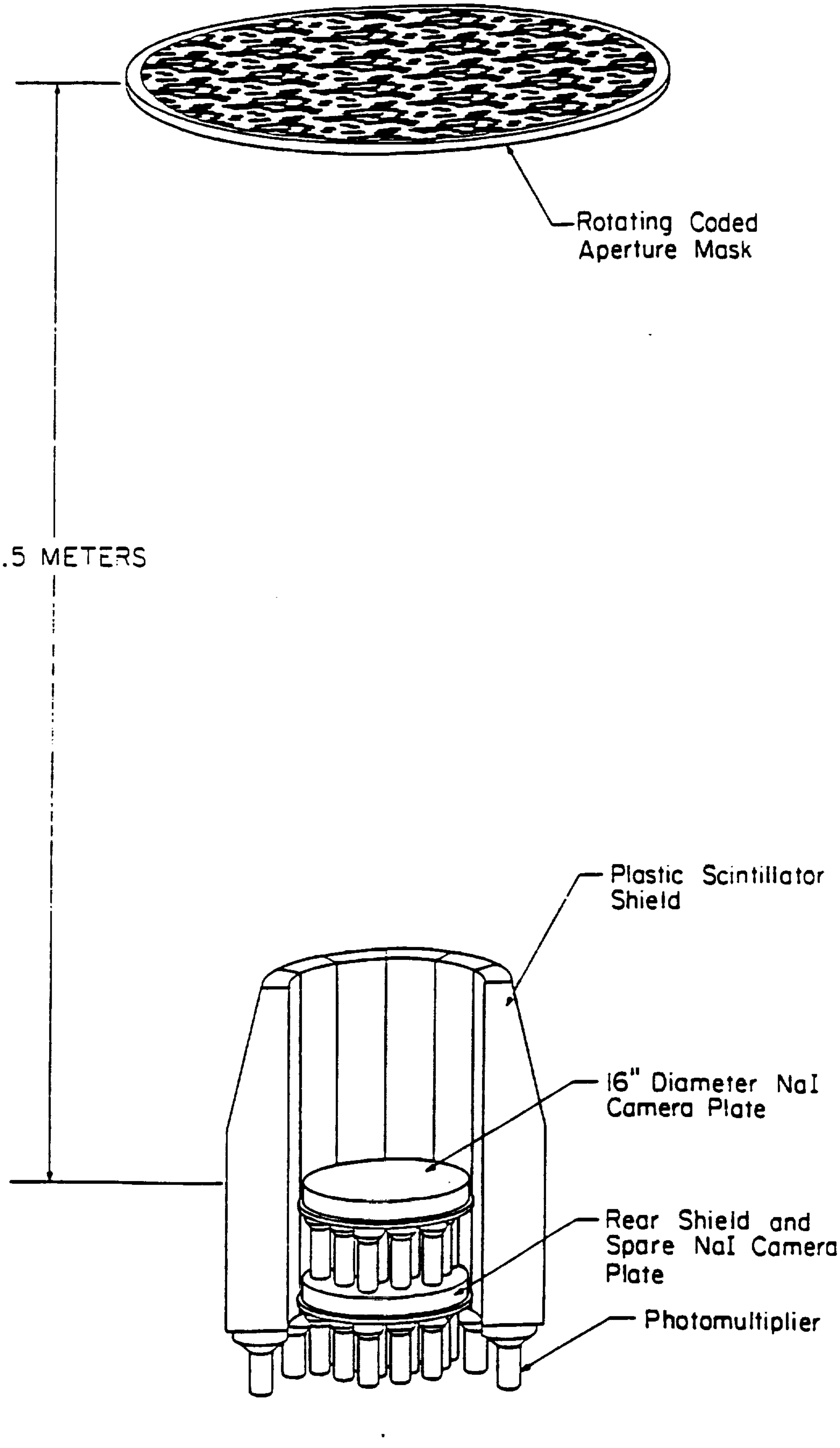


Figure 9: Basic elements of the GRIP instrument. Shown are the rotating HURA mask and the shielded detector system. The primary NaI(T1) detector is separated from the mask by 2.5 m. The primary detector is actively shielded by 12 plastic scintillator modules and a second NaI(T) detector.

source is one of the two most luminous γ-ray sources in the galaxy (comparable to Cyg X-1), very little is known about the system.

2.7 The High Energy Isotope Spectrometer Telescope (HEIST)

During the 1980's the SRL group developed a balloon-borne High Energy Isotope Spectrometer Telescope (HEIST) designed for high resolution measurements of isotopes of elements from Be to Ni ($4 \leq Z \leq 28$) at energies from ~0.4 to 2.0 GeV/nuc. The instrument, which has been a collaborative effort with the Danish Space Research Institute (DSRI) and the University of New Hampshire (UNH), consists of a stack of 12 NaI(Tl) scintillators of total thickness 88 g/cm^2, two Cerenkov counters (C1 and C2), and two plastic scintillators (see Figure 10). The basic technique employed by HEIST to measure mass is an accurate determination of the change in velocity undergone by a nucleus for a given change in kinetic energy. For example, a particle of charge Z and atomic number A has a mass M roughly given by $M = AM_n$, where M_n is an average nucleon mass. Since total energy E is given by $E = \gamma M$, where γ is the Lorentz factor, the change in γ due to an energy loss ΔE is given by $\Delta\gamma = \Delta E/M$. Thus,

$$A = \frac{\Delta E}{M_n \Delta\gamma},$$

and the determination of A depends on precise measurements of ΔE and $\Delta\gamma$. An innovative feature of HEIST is the use of the NaI crystals as both energy-measuring and trajectory-measuring devices. The total energy loss is obtained from the sum of the stack layers, and the ratios of the outputs of the PMTs viewing each layer are used to measure particle position to ~2 mm rms (for Fe).

The energy range covered by HEIST can be "tuned" by choice of the index of refraction (n) of the two Cerenkov counters. Isotope measurements of Fe from ~1.4 to ~2 GeV/nucleon obtained during a 1984 flight in the HEIST-1 configuration were reported at the Adelaide Cosmic Ray Conference. In its most recent version (HEIST-2; see Figure 10), C1 was composed of Teflon (n=1.34), C2 was composed of Pilot-425 (n=1.50), and the instrument was capable of resolving isotopes from Be to Ni over the energy range from ~0.4 to ~1.1 GeV/nucleon, with both improved mass resolution and yield over HEIST-1.

2.7.1 A Balloon Measurement of the Isotopic Composition of Galactic Cosmic Ray Iron

We have measured the isotopic composition of galactic cosmic ray iron in the energy interval ~1550-2200 MeV/nucleon using a balloon-borne mass spectrometer. The instrument was flown from Palestine, Texas, in May 1984 for >35 hours at an atmospheric depth of ~6 g/ cm^2. Masses were derived by the Cerenkov-Energy technique. The Cerenkov counter employed a silica aerogel radiator with index of refraction $n = 1.1$. Particle energies were measured in a stack of NaI(Tl) scintillators, which also provided particle trajectories. The calibration of the detectors is discussed, along with the algorithms we have used to calculate velocities, energies, and masses. The limitations of aerogels as Cerenkov radiators, particularly the stability of their light yield, are considered. A detailed discussion of the sources of mass uncertainty is presented, including an analytic model of the contribution from fluctuations in the Cerenkov yield from knock-on electrons. The achieved mass resolution is ~0.65 amu, which is consistent with the theoretical estimate. We report an $^{54}Fe/^{56}Fe$ abundance ratio of $0.14^{+0.18}_{-0.11}$ and 84% confidence upper limit of $^{58}Fe/^{56}Fe \leq 0.07$ at the top of the atmosphere. Combining our data with those of previous measurements of the composition of iron at lower energies, and using a model of the galactic propagation, we derive cosmic-ray source abundance ratios of $^{54}Fe/^{56}Fe = 0.064^{+0.032}_{-0.027}$ and $^{58}Fe/^{56}Fe \leq 0.062$. Our new measurement and earlier studies of the $^{54}Fe/^{56}Fe$ ratio are summarized in Table 2. These values are consistent with the composition of solar-system iron

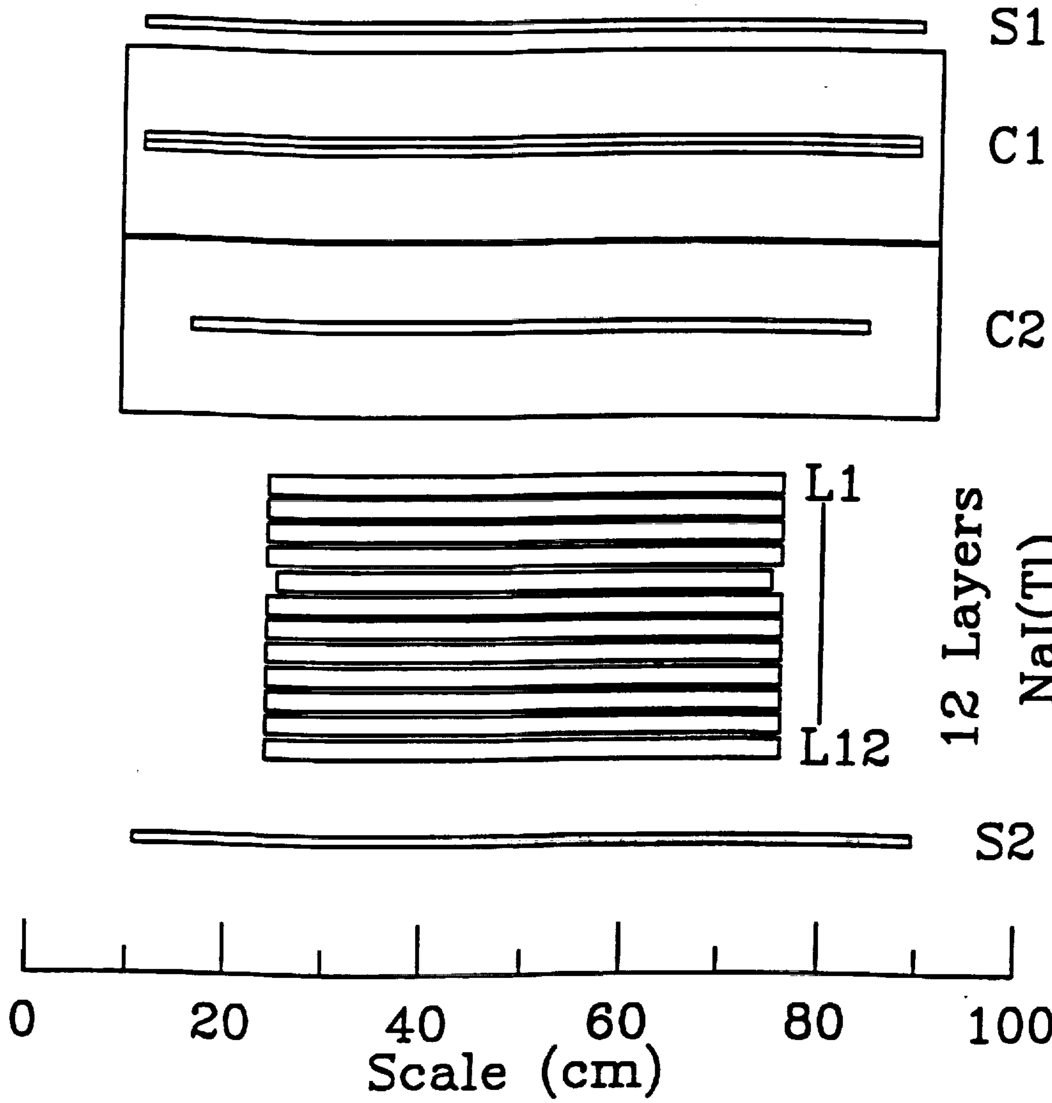


Figure 10: A cross section of HEIST including scintillators S1 and S2, Cerenkov counters C1 and C2, and NaI scintillator layers L1 to L12.

and place restrictions on the conditions under which cosmic-ray iron is synthesized.

Table 2 Summary of $^{54}Fe/^{56}Fe$ Measurements

Author	Energy(MeV/nuc)	Top of Atmosphere	GCRS
Tarle' *et al.*	~600-900	$\leq$0.11	$\leq$0.084
Mewaldt *et al.*	84-284	$0.11^{+0.091}_{-0.048}$	$0.085^{+0.096}_{-0.051}$
Young *et al.*	~600-900	0.10±0.032	0.077±0.032
Webber	~600-900	0.079±0.034	0.056±0.035
This work	~1550-2200	$0.14^{+0.18}_{-0.11}$	$0.12^{+0.18}_{-0.11}$
Average			$0.064^{+0.032}_{-0.027}$

2.7.2 The 1988 Balloon Flight and Data Analysis

On August 25 of 1988, HEIST-2 was launched from Prince Albert, Saskatchewan, where it floated for ~34 hours at an average altitude of 119,000 feet. The instrument operated perfectly over the entire flight and the number of events suitable for isotope analysis ranges from ~3000 for carbon to ~1000 for Mg to ~200 for Fe.

One of the features of HEIST is the use of redundant measurements. For each of the events above the C1 threshold there are at least two mass estimates: one from C1 - E_{tot} technique and one from the ΔE - E' technique using the NaI stack. Such redundant measurements to eliminate background due to particles which undergo nuclear interactions in the instrument. Figure 11 shows the mass histograms obtained for B, C, N, and O. The observed mass resolution is ~0.26 amu. Note that the observed abundances of radioactive species such as ^{11}C and ^{13}N are expected due to contributions from atmospheric secondaries.

The observed abundances of the various isotopic species are being determined using maximum likelihood fits to a weighted means of the various mass estimates. These observed abundances are then extrapolated to the top of the instrument, and then to the top of the atmosphere using a new semi-empirical cross section formula fit to carbon cross sections measured by W.R. Webber and colleagues at the Bevalac. To interpret these abundances at the top of the atmosphere we are using the propagation code that was instituted at Caltech in collaboration with W.R. Webber on a HEAO guest investigator grant, along with the latest measured and semi-empirical cross sections.

Figure 12 shows our HEIST measurements compared to earlier data and to results of the propagation calculations. Our HEIST data represent the highest energy direct isotope measurements to date (those >1000 MeV/nuc are based on *mean-mass* measurements). The ^{13}C measurements are particularly interesting in that they (along with the ISSE-3 data) favor a low $^{13}C/^{12}C$ ratio at the source, consistent with predictions of the Wolf-Rayet model. Note that our measurement (as well as the others in Figure 12) indicate an enhancement in the $^{18}O/16O$ ratio at the cosmic ray source by a factor of $\sim 6 \pm 2$, similar to that observed previously for $^{22}Ne/^{20}Ne$. This ^{18}O excess is a further example of the differences in nucleosynthesis between cosmic-ray and solar system material.

2.8 An Isotope Matter/Antimatter Experiment (IMAX)

IMAX is a balloon-borne instrument that is designed to measure the energy spectra of the isotopes ^{1}H, ^{2}H, ^{3}He and ^{4}He and the spectrum of cosmic ray antiprotons over the energy range

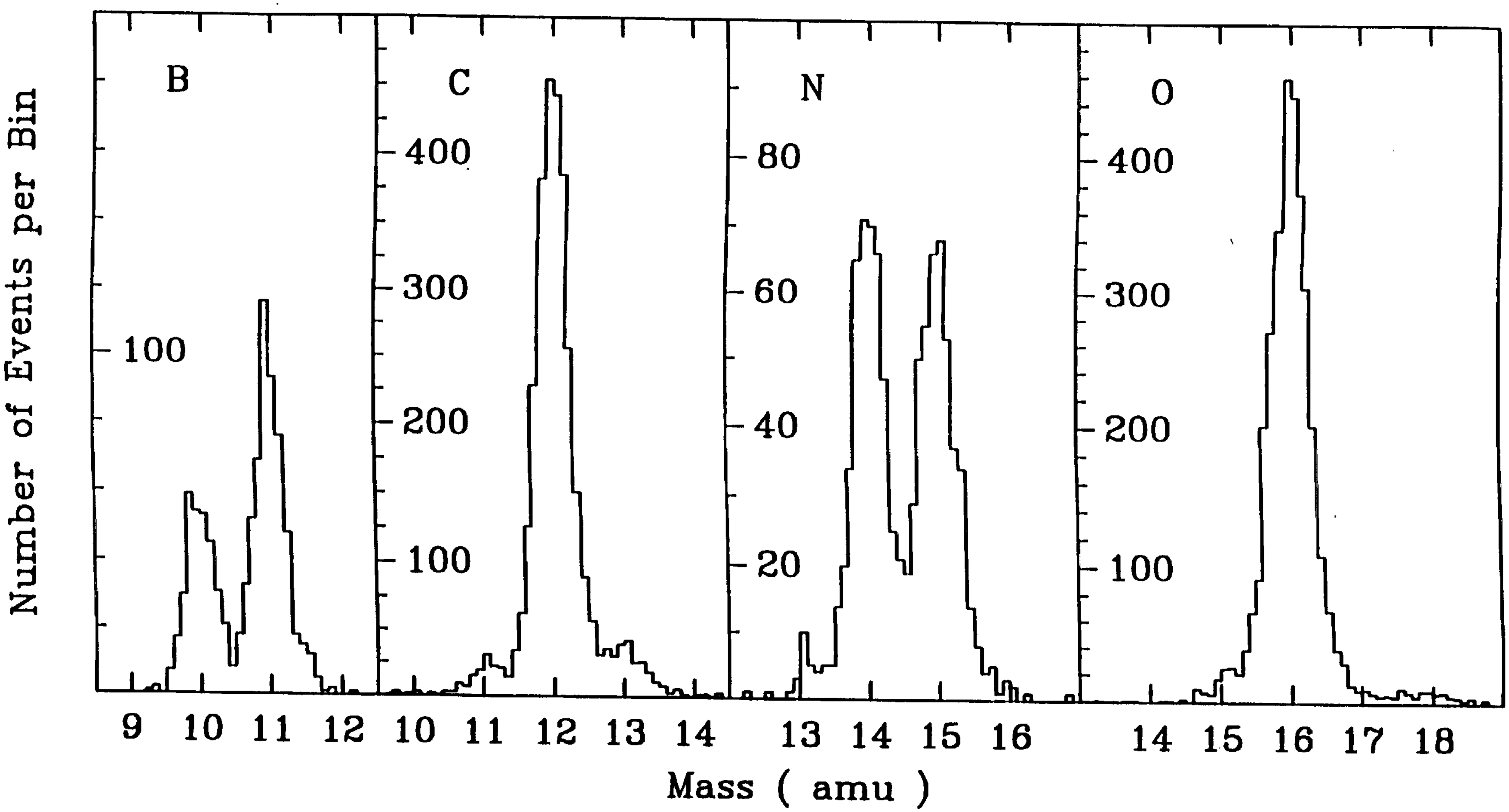


Figure 11: Mass histograms of B, C, N, and O nuclei.

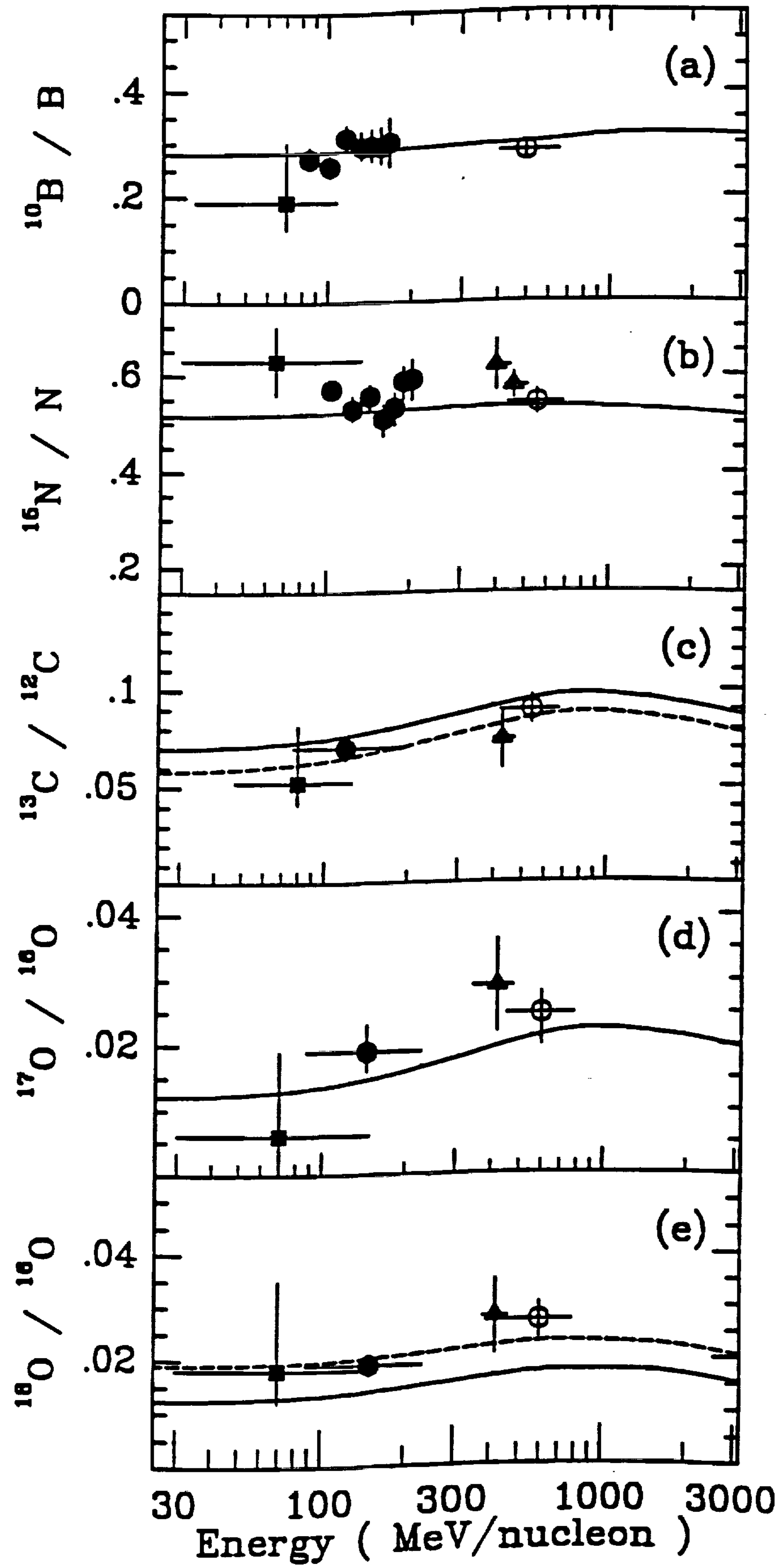


Figure 12: A comparison of collected cosmic ray isotope measurements having resolultion of 0.3 amu or better. HEIST data is shown as a open circle.

from 0.1 to 4 Gev/nucleon. It will also allow a sensitive search for anti-helium over this energy range. Measurements of the light H and the isotopes will test cosmic ray reacceleration and propagation models over a broad energy range and address the question of whether or not H and He in cosmic rays have a common origin and history with heavier cosmic rays. IMAX antiproton studies will test a variety of models designed to explain the excess of antiprotons observed at high energies in cosmic rays.

IMAX consists of a unique combination of Cerenkov, scintillation, and time-of-flight (TOF) velocity-measuring devices in combination with the NMSU Balloon-Borne Magnet Facility (BBMF), as shown in Figure 13. It is a collaborative experiment being carried out with scientists from Goddard, New Mexico State University, (DSRI), and the University of Siegen. Caltech, with help from GSFC and DSRI, is responsible for the design, fabrication and testing of the C2 and C3 Cerenkov Counters, which are based on aerogel radiators with indices of n=1.055 (C2) and n=1.025 (C3).

The first flight of IMAX is presently scheduled for the summer of 1992.

2.9 Summary of Balloon Flights

Table 3 summarizes the balloon flights of cosmic ray instruments that have been carried out under this grant and its predecessor. Table 4 includes a similar summary for the balloon flights conducted to detect cosmic gamma rays.

3.0 Laboratory Activities

3.1 The Solid State Detector Test and Calibration Facility

The facility for testing and calibration solid-state detectors began operation in 1972 and has been used continuously through 1990. This facility makes possible various particle and environmental tests on solid-state detectors (SSD's) which are of importance in selecting reliable, high-quality devices for use on spacecraft experiments.

The design philosophy of the facility was governed in part by the heavy anticipated demand for testing solid-state detectors (e.g., our cosmic-ray telescopes on the Voyager missions use 64 detectors) and in part by the existing solid-state detector technology.

Experience with SSD's accumulated over a period of more than two decades by members of this laboratory, has led to the formulation of a set of mainly empirical test and calibration procedures which allow us to select flight-worthy SSD's. We designed a new facility which provides for 1) a controlled and clean environment in which to do the tests and 2) adequate test equipment with which to evaluate the performance and reliability of a large number of detectors. These tests and calibrations are performed in a laboratory which has been converted to a "clean room". In this room, detectors are stored in a controlled dry nitrogen environment. The test equipment consists of 1) a thermal vacuum system which is used to assess the environmental reliability of the detectors, 2) a beta spectrometer which is used to evaluate the response of the detectors to monoenergetic electrons, 3) an alpha test system which is used to evaluate the response of the detectors to alpha particles, 4) a linear-flow clean bench, and 5) various electronic and optical instrumentation used in detector testing.

The clean room facilities have been used to test and calibrate detectors for the following space missions: IMP-8, Voyager 1/2, ISEE-3 (ICE), Galileo and SAMPEX.

3.2 PACE

The PACE multiparameter analysis system was developed by SRL to perform calibrations of a variety of detectors in the laboratory and in accelerator environments. The system provided the capability to pulse height analyze up to 16 simultaneous signals with a 13-bit ADC at event rates

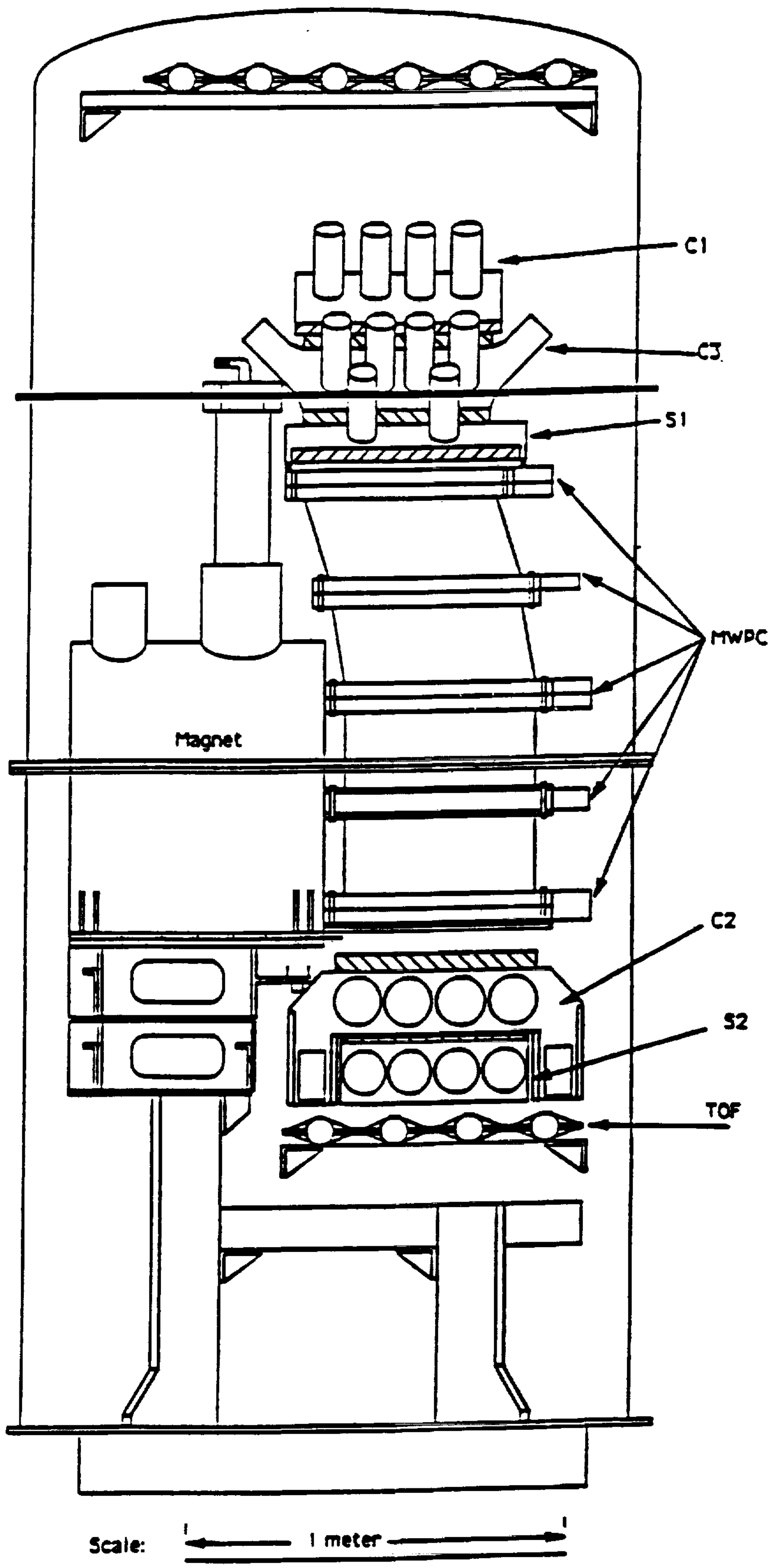


Figure 13: Schematic illustration of the proposed IMAX instrument in the NMSU magnet facility.

Cosmic Ray Balloon Program Table 3

Group Name: California Institute of Technology Space Radiation Laboratory

Name	Date Conceived	Dates Flown	No. Success	References
pαe (Proton alpha electron, spectrometer)	62	65 66 67 68 69 70	0* 6 7 2 5 1	Wenzel (1970) Garrard (1972) Garrard *et al.* (73a, 73b) Wenzel *et al.* (1975)
E (Electron Spectrometer)	64	67	5	Israel & Vogt (1968, 1969) Israel (1968, 1969)
E+ - (negatron) positron magnetic spectrometer)	66	68 69 70 71 73	3 3 2 2 0*	Beuermann *et al.* (1969, 1970) Beuermann (1971) Rice (1970) Cummings (1973) Cummings *et al.* (1973a, b, c, d)
PCIST (heavy isotope prop counter, CsI range telescope)	73	78	1	Wiedenbeck (1977, 1979) Zumberge (1981)
PBAR (antiproton antihelium spectrometer)	76	80	1	Buffington *et al.* (1981) Buffington & Schindler (1981a, b, 1983)
HEIST-1 (Z ≥ 20 isotopes, 1.5-2 GeV/nuc)	80	84	1	Buffington *et al.* (1981) Buffington *et al.* (1983) Schindler *et al.* (1983) Rasmussen *et al.* (1983) Christian *et al.* (1985) Lau (1985) Grove (1989) Grove & Mewaldt (1990, 1991)
HEIST-2 (4 ≤ Z≤ 26 isotopes, 0.4-1.3 GeV/nuc)	85	86 88	0* 1	Christian *et al.* (1987) Gibner *et al.* (in prep.)

*Balloon or balloon operations failures

Table 4

Name	Date Conceived	Dates Flown	No. Success	Activity
GRIP				
	82	85	0*	Palestine/Sel. Sources Viewed
(Gamma Ray		86	1	Palestine/Sel. Sources Viewed
Imaging		4/87&11/87	2	SN 1987A Campaign
Payload)		88	1	SN 1987A/Gal. Center
		89	1	SN 1987A/Gal. Center

*Balloon or balloon operations failures

up to ~10^4/sec. Data were stored in a buffer memory and recorded on magnetic tape. A portion of the data can be displayed in realtime on a storage scope.

PACE was first used in 1973 to perform calibrations of the IMP-8 telescope at Lawrence Berkeley Laboratory (LBL) 88-inch cyclotron. Although only eight parameters could be analyzed at once at that time, the capability of the system was later expanded to 16 parameters.

Over the years PACE was used at a variety of accelerators that included the Intelcom Rad. Tech. Electron Accelerator, the LBL Bevatron and Bevalac, and the Caltech Tandem van de Graaf. It was used to test and calibrate detector systems that were flown on IMP-8, Voyager 1 and 2, ISEE-3 (ICE), HEAO-3, and Galileo, as well as a variety a balloon experiments. An example of realtime data from PACE, showing the first example of heavy isotope resolution with silicon solid state detectors, appears below in Figure 14.

3.3 The Data Acquisition System, MACSYS

MACSYS is a data acquisition system for use in calibration of particle/photon detectors at accelerators such as the LBL Bevalac where running time is an extremely scarce and expensive commodity. Designed in-house with the support of this grant, it can acquire data from up to 24 (expandable) detectors simultaneously, allowing understanding of correlations between detectors as well as simultaneous calibration of multiple independent detectors at event rates of several thousand per second. It avoids the timing difficulties and non-linearities normally associated with peak-detect-and-hold circuitry and linear gate/delay line circuitry by running the 32 parallel ADCs constantly at 8 MHz. Since a charge-sensitive preamp/shaping amp combination will usually have a shaping time of 1 to 2 μsec, the pulse is sampled in excess of 10 times. A least squares fit of the (typically gaussian) shaping function to the measurements will yield, for example, baseline, peak height, and FWHM while digitally filtering noise. The fit is done in real time by a microprocessor, which then transmits the peak heights, etc. to a computer workstation, where the data are recorded and a real time display of the data allows verification by the user. The system was first used in May, 1990 for the SAMPEX detector testing and the HEAO cross section measurements. It was used in May 1991 for SAMPEX electron calibrations at EG&G Energy Measurements Facility in Santa Barbara and is being used at Caltech by SAMPEX, ACE, and other projects.

4.0 Activities Involving Experiments in Space

The major focus of SRL activities over the past two decades has been the design and development of instruments for spaceflight and the analysis and publication of data from these instruments. Both graduate students and post-doctrinal fellows have always played major roles in these activities. By supporting SRL and its staff and students, this grant has created and maintained the laboratory environment that has made it possible for flight projects to originate, develop, and come to fruition. We describe here briefly the space flight activities that have indirectly benefited from the support provided to SRL by this grant.

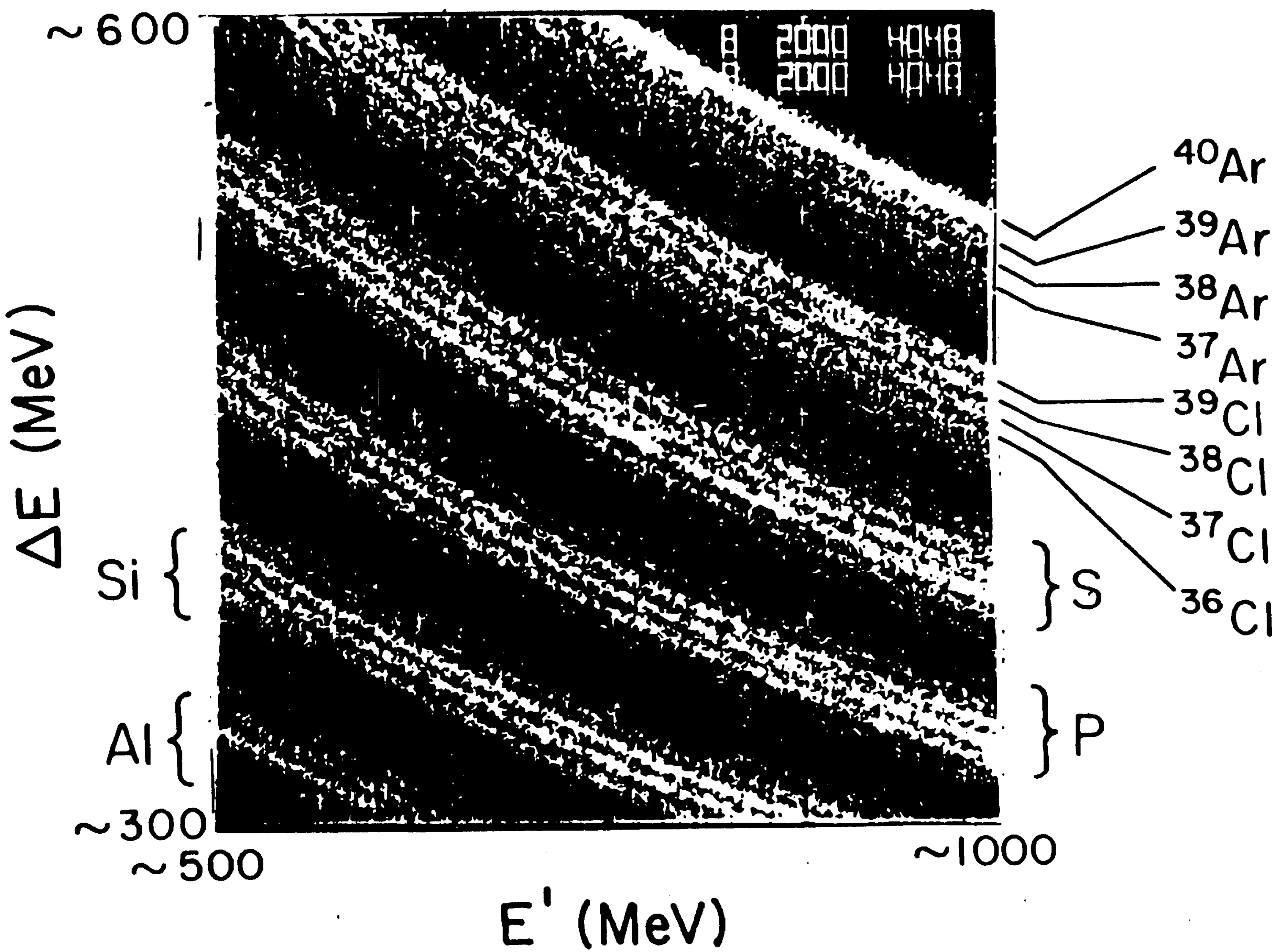
4.1 A Satellite Experiment Launched on OGO-4 on 28 July 1967.

This experiment, which was carried out jointly by E.C. Stone at Caltech and the Laboratory for Astrophysics and Space Research of the University of Chicago, measured the time-dependent energy spectra of protons (1 to 40 MeV), alpha particles (4 to 160 MeV) and electrons (0.4 to ~1 MeV) between July 1967 and January 1969.

4.2 A Solar and Galactic Cosmic Ray Experiment Launched on OGO-6 on 5 June 1969.

This experiment measured the differential energy spectra of protons and alpha particles between 1.2 MeV and 1 GeV/nucleon and of electrons between 280 KeV and 1.8 MeV. The differential measurements were extended to 15 GV by using the geomagnetic field. This broad

Figure 14


~600
~300
~500
~1000
ΔE (MeV)
E' (MeV)
Si
Al
S
P
40Ar
39Ar
38Ar
37Ar
39Cl
38Cl
37Cl
36Cl
0 2000 4048
0 2000 4048

energy range permits detailed studies of the solar modulation of galactic cosmic rays, the acceleration and interplanetary propagation of solar cosmic rays, and the penetration of charged particles into the magnetosphere.

4.3 An Electron/Isotope Spectrometer (EIS) Launched on IMP-7 in 1972 and on IMP-8 in 1973

These experiments are designed to measure the energy spectra of electrons and positrons (0.16 to ~6 MeV), and the differential energy spectra of the nuclear isotopes of hydrogen, helium, lithium, and beryllium (~2 to 50 MeV/nucleon). In addition, it provides measurements of the fluxes of the isotopes of carbon, nitrogen, and oxygen from ~5 to ~15 MeV/nucleon. The measurements from this experiment support studies of the origin, propagation, and solar modulation of galactic cosmic rays; the acceleration and propagation of solar flare and interplanetary particles; and the origin and transport of energetic magnetospheric particles observed in the plasma sheet, adjacent to the magnetopause, and upstream of the bow shock.

The extensive EIS data set has been utilized in comprehensive studies of solar, interplanetary, and magnetospheric processes. Correlative studies have involved data from other IMP investigations and from other spacecraft, including Voyager, Pioneer, ISEE-3 and COSMOS, as well as direct comparisons of EIS data from IMP-7 and IMP-8. We have recently been using data from our IMP-8 experiment to investigate the long term temporal history of anomalous oxygen at 1 AU over the years from 1972 to 1990, and we have been continuing our use of IMP data as a 1-AU baseline for collaborative gradient studies with the Pioneer and Voyager spacecraft in the outer heliosphere.

Tracking of IMP-7 was suspended during mid-1978, but tracking of IMP-8 is now planned to continue into the early 1990's.

4.4 An Interstellar Cosmic Ray and Planetary Magnetospheres Experiment (CRS) for the Voyager Missions Launched in 1977

This experiment is conducted by this group in collaboration with F. B. McDonald (University of Maryland), J. H. Trainor (Goddard Space flight Center), W. R. Webber (NMSU), and J. R. Jokipii (University of Arizona), and has been designated the Cosmic Ray Subsystem (CRS) for the Voyager Missions. The experiment is designed to measure the energy spectra, elemental and (for lighter elements) isotopic composition, and streaming patterns of cosmic-ray nuclei from H to Fe over an energy range of 0.5 to 500 MeV/nucleon and the energy spectra of electrons with 3 - 100 MeV. These measurements will be of particular importance to studies of stellar nucleosynthesis, and of the origin, acceleration, and interstellar propagation of cosmic rays. Measurements of the energy spectra and composition of energetic particles trapped in the magnetospheres of the outer planets are used to study their origin and their relationship to other physical phenomena and parameters of those planets. Measurements of the intensity and directional characteristics of solar and galactic energetic particles as a function of the heliocentric distance will be used for *in situ* studies of the interplanetary medium and its boundary with the interstellar medium. Measurements of solar energetic particles are crucial to understanding solar composition and solar acceleration processes.

The CRS flight units on both Voyager spacecraft have been operating successfully since the launches on August 20, 1977 and September 5, 1977. The CRS team participated in the Voyager 1 and 2 Jupiter encounter operations in March and July 1979, the Voyager 1 and 2 Saturn encounters in November 1980 and August 1981, the Voyager 2 Uranus encounter in January 1986, and the Voyager 2 Neptune encounter in August 1989. The Voyager data represent an immense and diverse data set, and a number of scientific problems are under analysis. These investigation topics range from the study of galactic cosmic-ray particles to particle acceleration phenomena in the interplanetary medium, to plasma/field/energetic particle interactions, to acceleration processes on the sun, to studies of elemental abundances of solar, planetary, interplanetary, and galactic energetic particles, and to studies of particle/field/satellite interactions in the magnetospheres of Jupiter, Saturn, Uranus, and Neptune.

The Caltech cosmic ray experiment on Voyager 2 (CRS) has been used to measure energetic charged particles trapped in the magnetic fields of the outer planets, as well as the interplanetary cosmic rays. By studying the radiation belts observed in the diverse settings found at the various outer planets and at the Earth, our potential for understanding the mechanisms which populate and maintain them is greatly enhanced.

As the decade of the 1990's begins the Voyagers look forward to their Interstellar Mission during which they may explore the solar wind termination shock, the heliopause, and possibly the nearby interstellar medium. If lucky, they may continue operating until ~2015, by which time they will be ~110-120 AU from the sun.

4.5 A Heavy Isotope Spectrometer Telescope (HIST) Launched on ISEE-3 in 1978

HIST is designed to measure the isotope abundances and energy spectra of solar and galactic cosmic rays for all elements from lithium to nickel ($3 \leq Z \leq 28$) over an energy range from several MeV/nucleon to several hundred MeV/nucleon. Such measurements are of importance to the study of the isotopic constitution of solar matter and of cosmic ray sources, the study of nucleosynthesis, questions of solar-system origin, studies of acceleration processes and studies of the life history of cosmic rays in the galaxy.

HIST was successfully launched on ISEE-3 and provided high resolution measurements of solar and galactic cosmic ray isotopes until December 1978, when a component failure reduced its isotope resolution capability. Since that time, the instrument has been operating as an element spectrometer for solar flare and interplanetary particle studies.

4.6 A Heavy Nuclei Experiment (HNE) Launched on HEAO-C in 1979

The HNE is a joint experiment involving the Caltech SRL, Washington University (M. H. Israel, J. Klarmann, and W. R. Binns), and the University of Minnesota (C. J. Waddington). The HNE was designed to measure the elemental abundances of relativistic ultraheavy cosmic-ray nuclei ($17 \leq Z \leq 130$). These data are relevant to studies of nucleosynthesis and stellar structures, the existence of extreme transuranic nuclei, the acceleration and propagation of cosmic rays, and the physical properties of the interstellar medium. HNE was successfully launched on HEAO-3 in 1979 and operated until 1981.

In addition to the data from the satellite itself, substantial amounts of data have been acquired in calibrations and cross-section measurements using heavy nuclei beams at the LBL Bevalac. The calibration data have been used to ensure confidence in our analysis of HNE data and have intrinsic interest in their relevance to scaling of ionization energy loss and Cerenkov radiation with charge. The cross-section measurements are important to the study of propagation of cosmic-rays through the interstellar medium. An understanding of this process is crucial to interpretation of many of the HNE results. This work is also improving our general understanding of the systematics of nucleus-nucleus interactions.

4.7 A Heavy Ion Counter (HIC) Launched on Galileo in 1989

The Galileo Heavy Ion Counter (HIC) was constructed by this group in collaboration with N. Gehrels at Goddard Space Flight Center. It will monitor penetrating (~10 to ~200 MeV/nucleon) sulfur, oxygen, and other heavy elements in the Jovian magnetosphere with the sensitivity needed to warn of potential "single-event upsets" (SEUs) in the spacecraft electronics. These upsets are changes in states of electronic components induced by ionizing radiation of a single energetic particle. Caltech is responsible for managing operations and data analysis for this instrument. Although the primary mission is engineering support, the data are of significant scientific value and will allow us to continue our investigation of the spectra of trapped ions in the Jovian magnetosphere and their relation to the Jovian aurora. In addition, during cruise (to the extent that coverage is available) and in the outer Jovian magnetosphere, we will use the instrument to measure the elemental composition of solar flare events and of the anomalous cosmic ray component. The measurements at 5 A.U. will be especially useful in the study of the radial dependence of the gradient of ACR oxygen.

4.8 A Solar and Magnetospheric Particle Explorer (SAMPEX)

In March of 1989 the Solar, Anomalous, and Magnetospheric Explorer (SAMPEX), on which we are co-investigators, was selected to be launched into polar orbit as part of the new Small Explorer (SMEX) program. SAMPEX is a collaboration between scientists at the University of Maryland (with G.M. Mason as P.I.), The Aerospace Corporation, Caltech, Goddard, and the Max-Planck Institut, and includes four instruments. Caltech, along with GSFC, will be responsible for furnishing a Mass Spectrometer Telescope (MAST), and a Proton Electron Telescope (PET) originally under construction for the (canceled) U.S. spacecraft of the International Solar Polar Mission (ISPM). These instruments will make new measurements of the isotopic composition of solar flare and anomalous cosmic rays with greatly improved collecting power, and will measure galactic cosmic ray isotopes and low-energy electrons. Among the unique measurements made possible by SAMPEX's polar orbit are a direct determination of the charge state of the anomalous cosmic ray component, and measurements of precipitating MeV electrons that may affect the atmospheric ozone balance.

Fabrication of MAST and PET is in progress with delivery to Aerospace for integration with the Data Processing Unit scheduled for September 1991. Launch is scheduled for June, 1992.

4.9 An Advanced Composition Explorer (ACE)

In 1989 the Advanced Composition Explorer (ACE) was selected as one of two new Explorer Class missions to be launched in the latter part of the 1990's. This investigation is conducted jointly by this group, (with E. C. Stone as P.I.) and by scientists from Applied Physics Lab/Johns Hopkins University, the University of Bern, the University of Chicago, Goddard Space Flight Center, Los Alamos National Laboratory, the University of Maryland, the University of New Hampshire and the Max-Planck Institut. Launch is currently planned for 1997. ACE will make comprehensive measurements of the elemental and isotopic composition and the charge states of accelerated nuclei with increased sensitivity of several orders of magnitude, and with improved mass and charge resolution. It will observe particles of solar, interplanetary, and galactic origins, spanning the energy range from that of the solar wind ($\sim$ 1 KeV/nucleon) to galactic cosmic ray energies (several hundred MeV/nucleon). Definitive studies will be made of the abundance of essentially all isotopes from H to Zn ($1 \leq Z \leq 30$), with exploratory isotope studies extending to Zr ($Z=40$).

The ACE study payload includes six high-resolution spectrometers, each designed to provide the ultimate charge and mass resolution in its particular energy range, and each having a collecting power 1 to 3 orders of magnitude greater than previous or planned experiments. Included in the study would be two spectrometers, a Solar Isotope Spectrometer (SIS), and a Cosmic Ray Isotope Spectrometer (CRIS), for which Caltech will play a leading role.

4.10 A Large Isotope Spectrometer for Astromag (LISA)

In 1989 the LISA experiment was selected as one of three experiments to fly on the Space Station with the Astromag facility for Particle Astrophysics. LISA is designed to measure the isotopic composition of heavy nuclei ($4 \leq Z \leq 28$) in the GeV/nucleon energy region, to search for heavy antinuclei, and to measure the energy spectra of individual heavy elements over 2 to 3 decades in energy with unprecedented precision. However in November of 1990 Astromag and other attached payloads were indefinitely postponed as part of the descoping of SSF. At this time, a study was initiated at GSFC in order to see if the LISA and Wizard experiments could be accomplished in a free-flying version of Astromag. SRL has participated in this study, helping to achieve a redesign of LISA optimized to be accommodated on an Atlas launch of Astromag into a 57° orbit.

LISA consists of a combination of Aerogel and Pilot Cerenkov detectors, plastic-scintillator time-of-flight counters. and scintillating optical fiber trajectory detectors arranged in modular fashion. This instrumentation will be provided by a team of investigators that is led by principal investigator J.F. Ormes and R.E. Streitmatter from Goddard Space Flight Center, M.E. Wiedenbeck from the University of Chicago, T.L. Garrard, R.A. Mewaldt and E.C. Stone from Caltech, W.R. Binns and J. Klarmann from Washington University, and I.L. Rasmussen from the Danish Space Research Institute. Caltech would have responsibility for the three different types of Cerenkov counters and for design and organization of the ground-based data analysis system.

5.0 Education

As part of one of the leading scientific institutions in the world, one of SRL's "missions" over the past two decades has been education, including the training of undergraduates, graduate students, and post-doctoral research fellows. Students and research fellows have always played an esential role in all of SRL's projects, particularly in the conceptual design, testing and calibration, and the data analysis phases. For those balloon-borne and laboratory studies supported by this grant students have themselves in many cases, designed and fabricated the actual flight hardware.

Table 5.1 lists that Ph.D's that have been awarded by SRL with the help of support by this grant. In addition, more than 200 Caltech undergraduate students have been employed by SRL over the period (see Table 5.2), either full time during the summer or part-time during the school year.

Table 5.1

GRADUATE THESES IN SRL - 1970 - 1989

"Propagation of 1-10 MeV Solar Flare Protons in Interplanetary Space," Murray, S.S., Ph.D Thesis, California Institute of Technology (1970).

"Magnetospheric Access of Solar Particles and the Configuration of the Distant Geomagnetic Field Lines ," Evans, L.C., Ph.D Thesis, California Institute of Technology (1971).

"Solar Flare Particle Propagation-Comparison of a New Analytic Solution with Spacecraft Measurements," Lupton, J.E., Ph.D Thesis, California Institute of Technology (1972).

"A Quantitative Investigation of the Solar Modulation of Cosmic-Ray Protons and Helium Nuclei," Garrard, T.L., Ph.D. Thesis, California Institute of Technology (1972).

"A Study of Cosmic Ray Positron and Electron Spectra in Interplanetary and Interstellar Space and the Solar Modulation of Cosmic Rays," Cummings, A.C., Ph.D. Thesis, California Institute of Technology (1973).

"A Satellite Measurement of Cosmic-Ray Abundances and Spectra in the Charge Range $2 \leq Z \leq 10$," Brown, J.W., Ph.D Thesis, California Institute of Technology (1973).

"Observations of Hydrogen and Helium Isotopes in Solar Cosmic Rays," Hurford, G.J., Ph.D Thesis, California Institute of Technology (1974).

"Observations of Nitrogen and Oxygen Isotopes in Low Energy Cosmic Ray," Vidor, S.B., Ph.D Thesis, California Institute of Technology (1975).

"The Streaming of 1.3-2.3 MeV Cosmic-Ray Protons During Periods Between Prompt Solar Particle Events," Marshall, F. E., Ph.D Thesis , California Institute of Technology (1976).

"An Investigation of Techniques for the Measurement and Interpretation of Cosmic Ray Isotopic Abundances," Wiedenbeck, M. E., Ph.D Thesis, California Institute of Technology (1977).

"Observations of 1-6 MeV Jovian Electrons at 1 AU and a Study of Their Propagation," Hartman, S.R., Ph.D Thesis, California Institute of Technology (1979).

"Elemental Composition of Solar Energetic Particles," III, W.R. Cook, Ph.D Thesis, California Institute of Technology (1980).

"A Balloon Measurement of the Isotopic Composition of Galactic Cosmic Ray Boron, Carbon, and Nitrogen," Zumberge, J., Ph.D Thesis, California Institute of Technology (1981).

"Energetic Oxygen and Sulfur Ions in the Jovian Magnetosphere," Gehrels, N., Ph.D Thesis, California Institute of Technology (1981).

"The Isotopic Composition of Energetic Particles Emitted from a Large Solar Flare," Spalding, J.D., Ph.D Thesis, California Institute of Technology (1982).

"The Relative Abundances of Sn,Te,Xe,Ba, and Ce in the Cosmic Radiation," Krombel, K., Ph.D. Thesis , California Institute of Technology (1983).

"Solar Photospheric and Coronal Abundances from Solar Energetic Particle Measurements," Breneman, H.H., Ph.D Thesis, California Institute of Technology (1985).

"A Cerenkov-ΔE-Cerenkov Detector for High Energy Cosmic Ray Isotopes and an Accelerator Study of ^{40}Ar and ^{56}Fe Fragmentation ," Lau, K.H., Ph.D Thesis, California Institute of Technology (1985).

"The Abundances of Ultraheavy Elements in the Cosmic Radiation," Newport, B.,

Ph.D. Thesis, California Institute of Technology (1986).

"The Imaging of Extra-Galactic Low-Energy Gamma-Ray Sources: Prospects, Techniques, and Instrumentation," Finger, M.H., Ph.D. Thesis, California Institute of Technology (1987).

"Evidence for Anomalous Cosmic Ray Hydrogen," Christian, E.R., Ph.D. Thesis (1989).

"A Balloon Measurement of the Isotopic Composition of Galactic Cosmic Ray Iron," Grove, J.E., Ph.D Thesis, California Institute of Technology (1989).

Table 5.2

UNDERGRADUATE STUDENTS EMPLOYED IN SPACE RADIATION LAB

NAME	DATES OF EMPLOY.
Ahern, Sean	4-90 to 5-91
Ahle, Larry	6-89 to 9-90
Allen, N. Charles	11-66 to 7-67
Ang, Mung-Ling	7-80 to 8-80
Bajura, Michael	1-86 to 6-86
Becker, Alex	10-84 to 6-85
Below, John F.	1-71 to 10-72
Bergman, Rodney	9-64 to 6-65
Bernstein, Noam	4-89 to 10-89
Bleck, Mark	4-72 to 6-73
Borland, Michael	3-82 to 9-82
Books, J.	6-64 to 9-64
Buck, Lester	12-73 to 6-74
Carr, Jeffrey	11-79 to 3-82
Carter, Eric	11-74 to 3-75
Casteel, Michael	9-66 to 6-68
Chai, King Long	6-76 to 10-76
Chan, Edward	2-77 to 6-77
Chang, Hsueh-Chia	3-73 to 6-75
Chang, Yiina	9-79 to 5-80
Cheng, Joe	6-82 to 10-82
Chiang, Terry Teh-I	3-78 to 6-78
Chivukula, R. Sekhar	1-80 to 6-80
Chou, Mike (SURF)	6-89 to 3-90
Codona, Johanan	4-78 to 2-79
Coleman, Phillip	9-63 to 8-66
Cooper, Robert	10-65 to 8-67
Copeland, Jeff	4-75 to 11-75
Cowan, Thomas E.	6-79 to 7-81
Dailey, Thomas	6-66 to 8-66
Davidson, Kris	6-64 to 6-65
Deane, John F.	7-80 to 10-80
Dimotakis, Paul	5-65 to 9-68
Draper, Denise	5-81 to 11-83
Dresser, Donald	9-66 to 9-67
Duesdieker, Giles	6-69 to 3-70
Dyer, Brian	10-76 to 6-77
Early, Stephen	5-71 to 6-71
Egwuatu, Alexander	12-73 to 2-74
Ennis, Joel B.	6-79 to 8-81
Erickson, Tim	3-75 to 6-75
Ethridge, Eric	4-78 to 1-80
Farrell, Walter	2-69 to 3-70
Fernandez, Michael	7-81 to 5-83
Finan G.	6-77 to 8-77
Fisher, Kim	5-72 to 9-72
Fong, Patrick	3-75 to 5-76
Freinkel, Carol	8-71 to 11-71
Garde, Shrikant	2-76 to 6-76
Gellman, Andrew J.	4-78 to 5-78
Ghamati, Saeid	10-79 to 1-80
Gibson, Merrill	2-75 to 9-75
Glavicano, J.	12-80 to 4-81
Goodwin, Peter M.	4-78 to 9-78
Gordan, Daniel M.	6-79 to 5-80
Gould, Thomas	7-86 to 9-86
Gralak, Raymond J.	10-79 to 11-79
Grennan, Steve	1-74 to 9-75
Gunter, Donald	5-69 to 10-71
Gustafson, Eric	4-73 to 6-74
Hamrick, Edward	5-76 to 6-77
Hansen, Gary	5-74 to 1-75
Hargreaves, Kirk	3-90 to 9-90
Harkness, Gregory	2-67 to 7-68
Harriman, Martin	12-75 to 4-76
Hartsfield, Rebecca	6-75 to 6-76
Hawkins, Bergendahl	1-75 to 2-75
Hawkins, Jonathan	6-89 to 9-89
Hayes, Brian (SURF)	6-87 to 10-88
Herman, Thomas	6-73 to 2-74
Heumann, John M.	6-69 to 10-70
Heuschen, Mark	4-75 to 9-75
Hickey, Neil	10-75 to 12-80
Ho, Francis	6-87 to 5-88
Holstege, Eric	4-78 to 12-80
Horn, James D.	8-79 to 10-79
Hu, Eugene	1-85 to 6-85
Hubbell, Earl	12-89 to 1-90
Huey, Hugo	1-74 to 9-74
Ibbetson, James	6-88 to 12-88
Ihas, Gary	9-66 to 6-67
Jankevics, Andy	6-74 to 6-75
Johnson, Steven	1-68 to 6-68
Johnston, Philip F.	4-76 to 5-77
Kay, Max	4-72 to 6-73
Kelley, Jr., Robert E.	4-81 to 6-82
Kidd, Matthew	1-90 to 6-90
King, Henry H-C	4-79 to 8-79
Koening, Richard J.	9-79 to 5-80
Kourilsky, Gregory	9-66 to 9-67
Kuyper, Jr., James	7-80 to 4-81
Lao, Lang	1-74 to 2-76
Leahy, Brian R.	1-80 to 6-80
Lee, Kevin	6-84 to 4-85
Lewis, Alan	2-71 to 6-71
Li, Kenneth	10-75 to 6-76
Li, Zhaohong	6-90 to 11-90
Lieberman, Barry	9-67 to 12-67
Lim, Hahn-Ren	6-89 to 10-89
Lindblad, Chris J.	3-80 to 8-80
Logan, Robert	6-66 to 9-66
Loughry, Thomas J.	1-77 to 11-78
Loverall, John C.	4-80 to 10-80

Manohar, Aneesh V.	1-80 to 9-81
Market, Thomas H.	5-70 to 8-70
Martin, Stephen	5-81 to 9-84
Maxwell, Craig	6-65 to 10-65
Mayhew, James R.	11-81 to 6-82
McElroy, Jason	3-90 to current
Megeath, S. Thomas	3-83 to 6-86
Melden, Gregory J.	9-79 to 1-80
Merkin, Leo	9-85 to 9-85
Meyer, Michael S.	5-78 to 5-79
Middleditch, John	5-67 to 9-67
Miller, William	1-70 to 1-71
Molzon, William	2-71 to 6-72
Munro, David	6-74 to 1-75
Nassir, Michael	10-90 to 10-91
Neerman, Keith	4-76 to 6-76
Neuberger, Kent L.	12-80 to 12-81
Ng, Johnny	12-86 to 3-87
Ngai, John Y-K	10-79 to 5-80
Nolan, Patrick	10-72 to 10-73
Offermann, Robert	1-70 to 6-71
O'Mahoney, Barry	1-78 to 5-78
Osheroff, Thomas	2-70 to 6-72
Parry, Christian S.	2-76 to 6-76
Pearson, Michael R.	1-80 to 7-80
Petruncola, Alex	5-71 to 8-73
Pham, Son Van	1-85 to 12-88
Pischel, Ken	2-69 to 4-69
Pope, Gary	11-70 to 6-73
Porter, Michael	5-76 to 1-78
Price, Channon	5-73 to 10-73
Prickett, Jr. Bruce	10-78 to 7-82
Radomski, Mark	6-67 to 10-69
Ramirez, Antonio	1-91 to 3-91
Roffmam, Burton	11-66 to 6-67
Rousseau, Kenneth V.	6-77 to 8-77
Ruby, Gary	4-68 to 6-69
Ruddell, Kevin	2-72 to 9-72
Ruzzo, Larry	4-66 to 6-68
Sacks, Richard	9-66 to 6-67
Saffman, Mark	8-75 to 9-75
Sahani, Maneesh	1-88 to 2-88
Sand, Paul	6-70 to 6-73
Savage, Kevin	6-68 to 3-69
Schleich, Kristin	5-77 to 9-77
Schofield, Norman	3-67 to 9-67
Sharma, Subhash	12-74 to 6-75
Shen, Hubert	1-74 to 10-75
Shlachter, Jack	2-73 to 1-74
Shumate, Allen	12-74 to 9-76
Smith, Glenn (SURF)	6-87 to 6-88
Smith, Harding	4-67 to 10-69
Spreitzer, Michael	3-77 to 9-77
Stark, Tony	5-74 to 6-75
Steinbach, Arden	6-67 to 9-68
Stevenson, John	6-69 to 4-70
Stoughton, Tom	10-74 to 6-76
Suchter, Richard	4-66 to 1-68
Sullivan, Robert	3-73 to 4-74
Szolovits, Peter	5-68 to 6-69
Takeuchi, Ichiro (SURF)	6-85 to 1-86
Todd, Craig	1-69 to 7-70
Toney, Mike	3-78 to 6-79
Tran, Minh	12-86 to 6-88
Tressel, Patricia	3-73 to 7-74
Tucker, Brett	1-71 to 6-72
Turner, Michael	6-68 to 9-68
Valdes, Ben	6-80 to 10-80
Van Eck, Timothy E.	4-79 to 10-79
Villani, Dan	2-66 to 6-66
Vogt, Nicole	6-84 to 4-87
Wang, Dennis	2-74 to 10-74
Warner, Leah	4-90 to 9-90
Watkins, Larry	10-69 to 6-70
Weber, Doug	11-74 to 4-78
Wendt, Christopher H.	2-79 to 9-81
Whitcomb, Stanley	10-70 to 6-73
Whitten, Greg	10-69 to 1-71
Widdoes, Larry	4-70 to 10-72
Woodford, Dale A.	1-79 to 6-79
Woodward, David	10-65 to 6-67
Woolley, Michael R.	11-76 to 6-78
Xiaojian, Yan	1-88 to 5-88
Zmuidzinas, Jonas	5-78 to 9-81

6.0 Community Service

Over the past two decades SRL personnel have devoted their time and talents to a wide range of activities in service to the NASA community, including the following:

American Physical Society Astrophysics Division (Chairman)

American Physical Society Cosmic Physics Division (Chairman, Treasurer)

Astronomy and Astrphysics Survey Committee

Balloon Borne Magnet Facility Advisory Committee - (Chairman)

Balloon Working Group

Cosmic and Heliospheric Management Operations Working Group

Cosmic Ray Program Working Group

Gamma-Ray Astronomy Program Working Group

Gamma-Ray Observatory Users Committe - (Chairman)

Heliospheric Science Working Group

High Energy Astrophysics Management Operations Working Group

International Cosmic Ray Conference (Program Co-Chairman)

Jet Propulsion Laboratory, Chief Scientist

JPL Advisory Council

NAS/NRC Committee on Space Astronomy and Astrophysics (CSAA)

NAS/NRC Committee on Solar and Space Physics (CSSP)

NAS/NRC Committee on Solar/Terrestrial Research (CSTR)

Physical Sciences Committee

Pinhole/Occulter Facility Science Working Group

Policy Board, Concurrent Supercomputing Consortium - (Chairman)

Solar System Exploration Committee

Space Physics Strategy/Implementation Study - (Panel Chairman)

Space Physics Subcommittee

Space Science Board

Superconducting Magnet Facility Definition Team

Supernova Science Working Group, Executive Committee

Voyager Project Scientist

X-Ray Program Working Group

7.0 Bibliography

A bibliography of the publications prepared under this grant is attached.

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