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SPACE RADIATION LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California 91125

SEMI-ANNUAL STATUS REPORT

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Grant NGR 05-002-160*
"RESEARCH IN PARTICLE AND GAMMA-RAY ASTROPHYSICS"

for

1 April 1987 - 31 March 1988

E. C. Stone, Principal Investigator
L. Davis, Jr., Coinvestigator
R. A. Mewaldt, Coinvestigator
T. A. Prince, Coinvestigator

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*NASA Technical Officer: Dr. W. Vernon Jones, High Energy Astrophysics

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Space Radiation Laboratory (SRL)
California Institute of Technology

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This report covers the research activities in Cosmic Rays, Gamma Rays, and Astrophysical Plasmas supported under NASA Grant NGR 05-002-160. The report is divided into sections which describe the activities, followed by a bibliography.

This group's research program is directed toward the investigation of the astrophysical aspects of cosmic rays and gamma rays and of the radiation and electromagnetic field environment of the Earth and other planets. We carry out these investigations by means of energetic particle and photon detector systems flown on spacecraft and balloons.

1. Particle Astrophysics

This research program is directed toward the investigation of galactic, solar, interplanetary, and planetary energetic particles and plasmas. The emphasis is on precision measurements with high resolution in charge, mass, and energy. The main efforts of this group, which are supported partially or fully by this grant, have been directed toward the following two categories of experiments.

1.1. Activities in Support of or in Preparation for Spacecraft Experiments

These activities generally embrace prototypes of experiments on existing or future NASA spacecraft or they complement and/or support such observations.

1.1.1. The High Energy Isotope Spectrometer Telescope (HEIST)

Over the past few years we have been developing a balloon-borne High Energy Isotope Spectrometer Telescope (HEIST) designed to make high resolution measurements of isotopes in the element range from H to Ni ($1 \leq Z \leq 28$) at energies from $\sim$0.4 to 2.0 GeV/nucleon. The instrument, which is a collaborative effort with the Danish Space Research Institute and the University of New Hampshire, consists of a stack of 12 NaI(Tl) scintillators of total thickness 88 g/cm^2, two Cerenkov counters (C1 and C2), and two plastic scintillators. HEIST determines the mass of individual nuclei by measuring both the change in the Lorentz factor ($\Delta\gamma$) that results from traversing the NaI stack, and the energy loss (ΔE) in the stack, and is designed to achieve a typical mass resolution of 0.25 amu.

The energy range covered by HEIST can be "tuned" by choice of the index of refraction (n) of the two Cerenkov counters. In its initial configuration (HEIST-1), flown in 1984, the top counter (C1) was composed of aerogel (n=1.10), giving an energy range of ~1.5 to 2 GeV/nucleon. In its present configuration (HEIST-2) C1 is composed of Teflon (n = 1.33) and C2 is Pilot 425 (n = 1.50) and the instrument is 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 the initial version of the instrument.

The new Cerenkov counters for HEIST-2, developed in collaboration with W. R. Webber of the University of New Hampshire, have significantly improved light yield, a result of considerable progress in several areas of Cerenkov counter development. In particular, improvements were made in wave-shifting and high-reflectance painting techniques, and a new Teflon "sandwich" radiator was developed that optimizes the output of C1. These developments were reported at the Moscow International Cosmic Ray Conference. Other improvements in HEIST-2 include a commandable high-gain mode, normally used for testing with ground-level muons, that can be used in flight to provide measurements of H and He isotopes with several hundred MeV/nucleon.

HEIST-2 was readied for balloon flight during the summer of 1986 and was launched from Ainsworth, Nebraska on September 7, 1986. Although the instrument was working well following launch, the balloon burst at ~70,000 feet, and the instrument suffered some damage on landing. A planned reflight of the instrument during 1987 had to be delayed because of the Australian balloon flights by our GRIP gamma ray experiment to image supernova 1987A and we have therefore been working towards a flight of HEIST-2 from Canada during the coming summer.

The repairs of damage to the pressure vessel and to the scintillator and Cerenkov counters are now complete, and a Pilot-425 radiator was substituted for fused silica in order to provide improved light yield. The entire detector system and flight electronics have been up and running for some time. The trigger logic has been modified and tested to allow for more efficient rejection of unwanted helium nuclei, and the microprocessor-based experiment controller has been tested at a higher clock frequency that would increase the instrument's live time. Still underway are refurbishments of the data recording system, the landing platform, the flight insulation, and the evaporative cooler and gas makeup systems. We remain on schedule to ship the instrument to Prince Albert, Canada in early July.

During November of 1987 the two Cerenkov counters for HEIST-2 were calibrated at the Lawrence Berkeley Laboratory Bevelac in beams of N, Ne, Ar, and Fe nuclei. In particular, the response of the 16 individual tubes of both counters was "mapped" with 1700 MeV/nuc Fe nuclei using laboratory multi-wire proportional counters to provide ~1 mm position resolution. In addition, the energy response of the counters was calibrated over the range from ~100 to ~1700 MeV/nucleons. These calibrations will be compared to calculations by graduate student Eric Grove, who has recently investigated various contributions to the velocity response and resolution of Cerenkov counters, including the effects of delta-ray production, and fluctuations in the number of delta-rays produced.

The focus of the Ph.D. thesis of graduate student J. E. Grove is the analysis of the data from the 1984 flight of HEIST-1. During the past year he has concentrated his efforts in understanding and mapping the response of the aerogel Cerenkov counter, and on developing algorithms for velocity and mass determination. The aerogel Cerenkov counter was mapped to an accuracy of ~1% with high energy ^{55}Mn nuclei at the Bevelac in November of 1982. Unfortunately, during the time between the Bevalac calibration and the balloon launch there was a gradual degradation in the light output of the aerogel by almost a factor of two that was not realized at the time, but is now being attributed to contamination of the aerogel by outgassing products of the $BaSO_4$ paint used in the light intergration box. Because it is possible that the degradation has compromised the accuracy of the Bevelac maps we have used flight data to check the Cerenkov maps. The rms deviation between the flight maps and the Bevalac maps amounts to less than 2.5%. Flight data have also been used to normalize the response of the 16 segments that make up the aerogel mosaic. Using relativistic Fe nuclei we believe that this block-to-block normalization is good to an accuracy of 1.5%.

We have now developed a new algorithm for velocity determination that makes use of the Cerenkov to ionization (C/I) ratio, which has the advantage that it is less sensitive to errors in the angle determination. We have also developed a method of correcting the energy-loss analysis in the NaI stack for the effects of saturation in the response of the NaI. When these algorithms are applied to the Bevalac calibration data a mass resolution of ~0.4 amu has been demonstrated for ^{55}Mn nuclei. We are now getting ready to apply these algorithms to the flight data, concentrating on the ~50 Fe nuclei that have been identified to have slowed down and stopped in the NaI stack without interacting.

During the November 1987 Bevalac calibration we also investigated the response of several new test samples of aerogel supplied by Ib Rasmussen of Danish Space Research Institute. These samples had indices of refraction ranging from 1.08 to 1.15. Among the properties that were tested were the overall light yield, the self-absorption of Cerenkov light, the uniformity of the index of refraction, and the amount of light produced by particles below the Cerenkov threshold.

Our work on HEIST has resulted in the following recent talks and papers:

- "High Resolution Cerenkov Detectors for Use in a Cosmic Ray Isotope Spectrometer ," Christian, E. R. et al., *Proceedings of the 20th International Cosmic Ray Conference, Moscow, USSR* **2**, 382 (1987).

In addition to our work on HEIST, we also devoted considerable effort during the past year to defining the goals and capabilities of Astromag, the proposed superconducting magnet facility for particle astrophysics on the Space Station. In particular, we have addressed the use of Astromag to measure the isotopic composition of high energy cosmic rays using the magnet/Cerenkov method, an approach that draws heavily on our experience with aerogel Cerenkov counters in HEIST. Some of the work was reported in a paper submitted to the Venice Conference on Physics and Astrophysics in the Space Station Era.

- "A Particle Astrophysics Magnet Spectrometer Facility for Space Station," Ormes, J. F. et al., *Proceedings of the 20th International Cosmic Ray Conference, Moscow, USSR* **2**, 378 (1987).

- "Galactic Cosmic Ray Isotope Spectroscopy: Status and Future Prospects," Mewaldt, R. A., *Proceedings of the 13th Texas Symposium on Relativistic Astrophysics*, p. 573, World Scientific, Singapore (1987).

- "Galactic Cosmic Ray Isotope Spectroscopy from the Space Station," Mewaldt, R. A. and J. F. Ormes, Invited talk presented at Conf. on Physics and Astrophysics in the Space Station Era, Venice, Italy, October 1987 (1988).

1.1.2. Low Energy Isotope Spectroscopy

In February of 1988 we learned that our proposal to the Explorer Concept Study Program for an Advanced Composition Explorer (ACE) was one of four proposals selected for a phase-A study. This investigation was proposed jointly by this group, 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, and the Max-Planck Institut. ACE would 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 would 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 would 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 five 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 would play a leading role. The phase-A study of ACE began in May of 1988, and is scheduled to be completed in one year.

In December of 1987 we submitted a proposal to NASA for an Energetic Particle Isotope Experiment (EPIX) to fly on the Air Force STARSCAN mission. EPIX would make significant advances in measuring the isotopic composition of solar energetic particles, galactic cosmic rays, and the anomalous cosmic-ray component, including elements from H to Ni ($Z = 1$ to 28) with energies > 10 MeV/nuc. The instrument designed to perform these measurements, EPIX, is comprised of two complementary telescopes, MAST and PET, originally approved and under construction as part of the Comprehensive Particle Analysis System (COMPAS) that was to have flown on the U. S. spacecraft of the International Solar Polar Mission (ISPM). In collaboration with Goddard Space Flight Center, we proposed to complete MAST and PET, and fly them on the STARSCAN mission planned for launch into a polar orbit in 1991. Because of its broad energy coverage, excellent mass resolution, and improved collecting power, over previous and planned missions, EPIX is especially well-suited for this "mission of opportunity", with the promise of significant advances in three separate areas of energetic particle spectroscopy, including some unique investigations that make use of the Earth's magnetic field. Although we now understand that the Air Force STARSCAN mision has been delayed, we remain interested in this or any similar opportunity to fly this instrumentation.

1.2. Experiments on NASA Spacecraft

The SR&T grant program of the Space Radiation Laboratory is strengthened by and contributes to the other programs described here. Activities related to these programs are primarily funded by mission-related contracts but grant funds are used to provide a general support base and the facilities which make these programs possible.

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

This experiment is 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, as well as direct comparisons of EIS data from IMP-7 and IMP-8.

We have also 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 1988. At the December AGU meeting we reported that the flux of 8-27 MeV/nuc anomalous oxygen in early 1987 did return to the same level as in the 1976 solar minimum, contrary to earlier predictions of some models. From the observed correlation between the flux of anomalous oxygen and the Mt. Washington neutron monitor, it is possible to estimate the flux of anomalous oxygen in 1984 and 1985 when several Spacelab experiments attempted to measure the charge state of anomalous oxygen using the Earth's magnetic field. It now appears that these experiments are not inconsistent with the prediction of Fisk, Ramaty and Koslovsky that the anomalous component is singly ionized.

Our studies of IMP data have resulted in the following recent papers:

- "Cosmic Ray Studies Out of the Ecliptic," Stone, E. C., *Proceedings of the 20th International Cosmic Ray Conference, Moscow, USSR* (1987).
- "Large-Scale Radial Gradient of Anomalous Cosmic-Ray Oxygen from 1 to ~ 30 AU," Cummings, A. C. et al., *Proceedings of the 20th International Cosmic Ray Conference, Moscow, USSR* **3**, 425 (1987).
- "Composition, Gradients, and Temporal Variations of the Anomalous Cosmic-Ray Component," Cummings, A. C. and E. C. Stone, Solar Wind VI Conference in Estes Park, Colorado (1987).

1.2.2. An Interstellar Cosmic Ray and Planetary Magnetospheres Experiment for the Voyager Missions Launched in 1977.

This experiment is conducted by this group in collaboration with F. B. McDonald and J. H. Trainor (Goddard Space flight Center), W. R. Webber (University of New Hampshire), 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 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, in the Voyager 1 and 2 Saturn encounters in November 1980 and August 1981, and in the Voyager 2 Uranus encounter in January 1986. 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, and Uranus.

Preparations are now being made for the Voyager 2 encounter with Neptune in 1989.

The following publications and papers for scientific meetings, based on Voyager data, were generated:

- "Satellite Signatures and Origins of Energetic Electrons at Uranus," Cooper, J. F. and E. C. Stone, *EOS Trans. AGU* **68**, 390 (1987).

- "Elemental Composition of the Local Interstellar Medium as Derived from Measurements of the Anomalous Cosmic Ray Component," Cummings, A. C. and E. C. Stone, *Bull. of Amer. Phys. Soc.* **32**, 1066 (1987).

- "Cosmic Ray Studies Out of the Ecliptic," Stone, E. C., *Proceedings of the 20th International Cosmic Ray Conference, Moscow, USSR* (1987).

- "Large-Scale Radial Gradient of Anomalous Cosmic-Ray Oxygen from 1 to ~ 30 AU," Cummings, A. C. et al., *Proceedings of the 20th International Cosmic Ray Conference, Moscow, USSR* **3**, 425 (1987).

- "Energy Spectra of Anomalous Cosmic-Ray Oxygen During 1977-1987," Cummings, A. C. and E. C. Stone, *Proccedings of the 20th International Cosmic Ray Conference, Moscow, USSR* **3**, 421 (1987).

- "Radial and Latitudinal Gradients of Anomalous Cosmic-Ray Oxygen and Helium and Galactic Cosmic Rays in the Outer Heliosphere," Cummings, A. C. et al., *Proceedings of the 20th International Cosmic Ray Conference, Moscow, USSR* **3**, 417 (1987).

- "Elemental Composition of the Anomalous Cosmic-Ray Component," Cummings, A. C. and E. C. Stone, *Proceedings of the 20th International Cosmic Ray Conference, Moscow, USSR* **3**, 413 (1987).

- "Composition, Gradients, and Temporal Variations of the Anomalous Cosmic-Ray Component," Cummings, A. C. and E. C. Stone, Solar Wind VI Conference in Estes Park, Colorado (1987).

- "The Voyager 2 Encounter with Uranus," Stone, E. C., *J. Geophys. Res.* **92**(A13), 14,873 (1987).

- "Voyager at Uranus," Stone, E. C. and E. D. Miner, *J. Br. Interplan. Soc.* **41**, 49.

- "Evidence for Anomalous Cosmic Ray Hydrogen," Christian, E. R. et al., *Bull. of Amer. Phys. Soc.* **33**(4), 1068 (1988).

- "Elemental Composition of the Anomalous Cosmic Ray Component and Implications for the Local Interstellar Medium," Cummings, A. C. et al., *Bull. of Amer. Phys. Soc.* **33**(4), 1069 (1988).

We describe below some of the work being done on gradients in the heliosphere.

Large-Scale Gradients of Anomalous Cosmic-Ray Oxygen

The anomalous cosmic-ray component is characterized by anomalous enhancements in the fluxes of helium, carbon, nitrogen, oxygen, neon, and argon with energies of ~5 to ~50 MeV/nucleon. Recognition that these elements have high first ionization potentials (except carbon which has a very small enhancement) and are therefore neutral in the local interstellar medium led to the widely held model in which anomalous cosmic rays originate as neutral interstellar atoms that drift into the heliosphere, become singly-ionized near the Sun, and are then convected outward by the solar wind to the outer heliosphere where the ions are accelerated to higher energies.

Early studies of the gradients of anomalous cosmic rays were based on observations made essentially in the ecliptic plane, except for one important period in 1976 when Pioneer 11 reached ~16° N latitude. The only other spacecraft to reach significant latitudes is Voyager 1 and it began to climb out of the ecliptic plane after its encounter with Saturn in 1980. By the beginning of 1987 it had reached 28°N heliographic latitude.

In Figure 1 we show the flux of anomalous oxygen as observed by Voyagers 1 and 2 in the energy region from 5.6 - 17.2 MeV/nuc from 1983 to 1987. Note that the Voyager 1 flux drops below that of Voyager 2 in early 1985 even though Voyager 1 is farther out from the Sun. In the inset to Figure 1 we show the near-Sun current sheet tilt data shifted in time to account for the propagation delay to the position of Voyager 1, using a solar wind speed of 500 km/sec. The crossover in fluxes corresponds to the time when the predicted current sheet tilt drops below the latitude of Voyager 1, suggesting that when Voyager 1 samples from only one side of the current sheet, a negative latitudinal gradient can be observed.

In order to separate radial and latitudinal gradients, we need more than just two spacecraft. Recently, we have added data from Pioneer 10, Pioneer 11, and IMP-8, which is at 1 AU, to the Voyager data in order to derive both the radial and latitudinal gradients.

We will suggest later that heliomagnetic coordinates may well be the most natural set of coordinates to use for describing the gradients. However, we have no direct measure of the heliomagnetic latitude of the spacecraft, and so in what follows we use heliographic coordinates instead. Note, however, that a change in the tilt of the current sheet results in a change in the heliomagnetic latitude of the spacecraft which could lead to a change in the derived heliographic gradient.

The data for the period 1986 day 156 to 1987 day 53 are shown in Figure 2. The radial gradient apparently decreases with distance, as shown by the dashed line connecting the flux values from IMP-8, Voyager 2, and Pioneer 10, all of which are near the heliographic equator. The gradient from 1 to 20 AU is ~16%/AU, consistent with measurements in the inner heliosphere in the last half of the solar cycle. In the outer heliosphere, from 20 to 40 AU, the gradient is much smaller, ~3%/AU. During the last solar minimum all spacecraft were inside 20 AU, so there are no outer heliospheric data with which to compare.

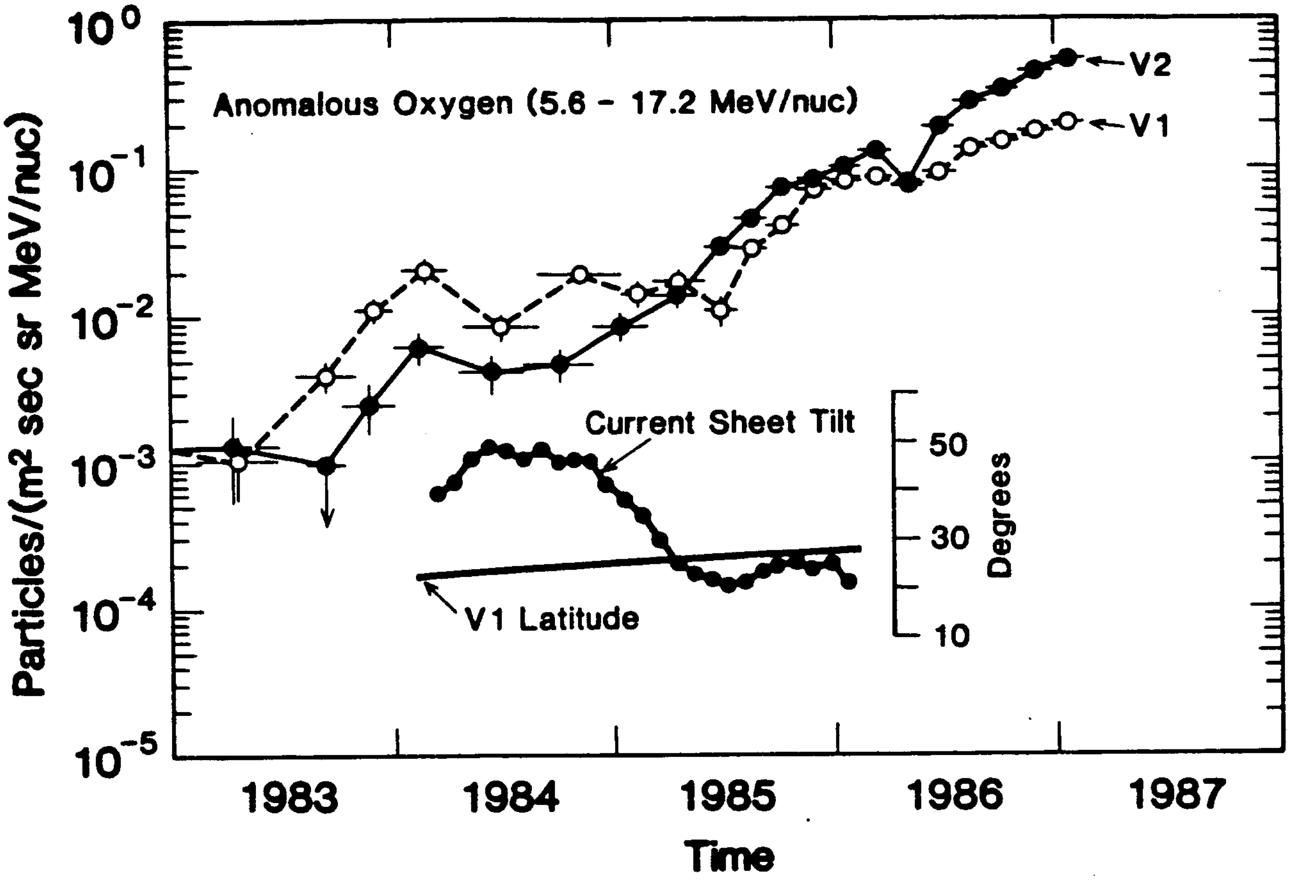

Figure 1

The abrupt change in the gradient at ~20 AU, as depicted in Figure 2, is rather unlikely. We have explored several smooth functions that have some physical basis. For example, Figures 3a and b show least-squares fits to the data assuming a constant latitudinal gradient and a radial gradient which is proportional to r^n. Figure 3a shows the radial dependence of the flux after correcting for the latitudinal gradient, and Figure 3b shows the latitudinal dependence of the flux corrected to 20 AU. The best-fit value of n is -1.0 and the latitudinal gradient is -4.3%/deg. We find that this value of the latitudinal gradient is essentially independent of the assumed radial gradient function. A non-linear latitude dependence, such as that shown by the dashed line in Figure 3b, cannot be ruled out, however.

The 1/r dependence for the radial gradient might be plausible if the particles are drifting in along the current sheet and diffusing perpendicular to the sheet with a $\kappa_\perp$ which varies inversely with the magnetic field strength. With this radial dependence, the gradient would be ~ 60%/AU from 1 to 3 AU, much larger than observed in the previous solar minimum. However, it is also possible that the gradient more nearly resembles the dashed line in Figure 2, possibly reflecting a change in the structure in the interplanetary medium, such as the merging of interaction regions beyond ~10 AU.

Two suggestions for the origin of the negative latitudinal gradient have been discussed recently. The first is that the decreased flux at Voyager 1 is due to increased

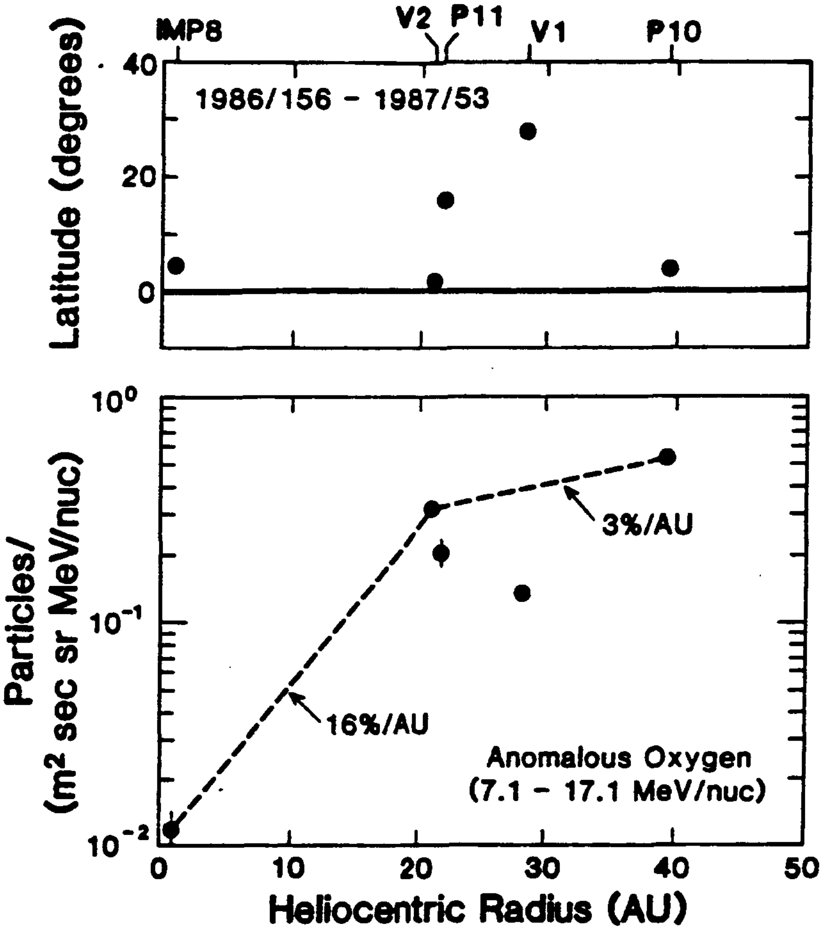

Figure 2

convective effects resulting from a positive latitudinal gradient in the solar wind speed. It has been noted, however, that a positive latitudinal cosmic ray gradient would result unless special assumptions were made concerning the radial dependence of the diffusion coefficient. The second suggestion is that the latitudinal gradient is a natural consequence of the boundary condition at the neutral current sheet assuming that drift effects are important in cosmic-ray propagation.

It is difficult to distinguish between these two possibilities during the current half-cycle because both could lead to negative latitudinal gradients. However, during the last half of the solar cycle the drift gradient should have been positive due to the reversed magnetic polarity, while a solar wind induced gradient would have again been negative. A positive latitudinal gradient in the anomalous helium flux was observed in 1976 by University of Chicago experimenters when Pioneer 11 reached 16° latitude and was above the current sheet most of the time. Thus a gradient reversal appears to have occurred with the reversal of the solar magnetic field, as expected if the gradient arises from drifts.

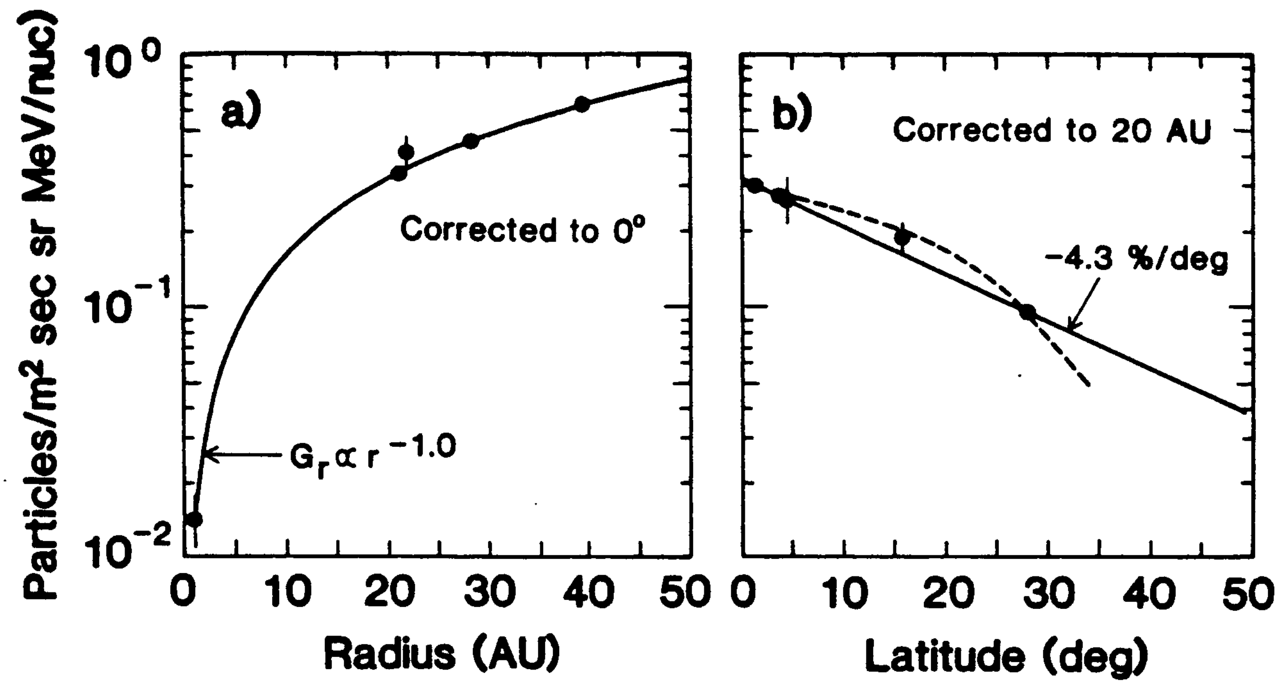

Figure 3

Recurrent variations in the Voyager 1 counting rates may also indicate that the latitude gradient is with respect to the current sheet, rather than the heliographic equator. In Figure 4a we show the Voyager 1 and 2 counting rates of nuclei with >70 MeV/nuc for 1986 and 1987. After the large Forbush decrease in early 1986, there are large recurrent 26-day variations in the Voyager 1 rate that are absent or much smaller in the Voyager 2 rate. Even larger recurrent variations are present in the Voyager 1 fluxes of anomalous oxygen, shown in Figure 4b, which are again much larger than in Voyager 2.

Recently such variations in the >70 MeV/nuc rate, along with the general recovery profile of the rate from 1981 through 1984, have been attributed by other workers to the passage of enhanced magnetic field regions past the spacecraft. These regions are presumed to contain enhanced turbulence, leading to a decreased diffusion coefficient from the position of the observer to the modulation boundary. The force-field approximation for the cosmic-ray transport equation was used by those workers to predict the recovery profile of the Voyager 2 cosmic-ray rate based on the measured magnetic field profile at the spacecraft. Although this approach resulted in general agreement of the predicted and measured cosmic-ray rate profiles, it remains to be seen whether such a technique will be able to account for the very different profiles at the two spacecraft observed in 1986-1987 as shown in Figure 4a.

An alternate explanation for the variations seen in Figures 4a and b is that they reflect a combination of a gradient in magnetic latitude together with a variation in the latitude caused by a wavy current sheet. The amplitude of the intensity variations is determined by the magnitude of the tilt of the current sheet, α, and the magnitude of the local latitudinal gradient in the vicinity of the spacecraft. If we define the

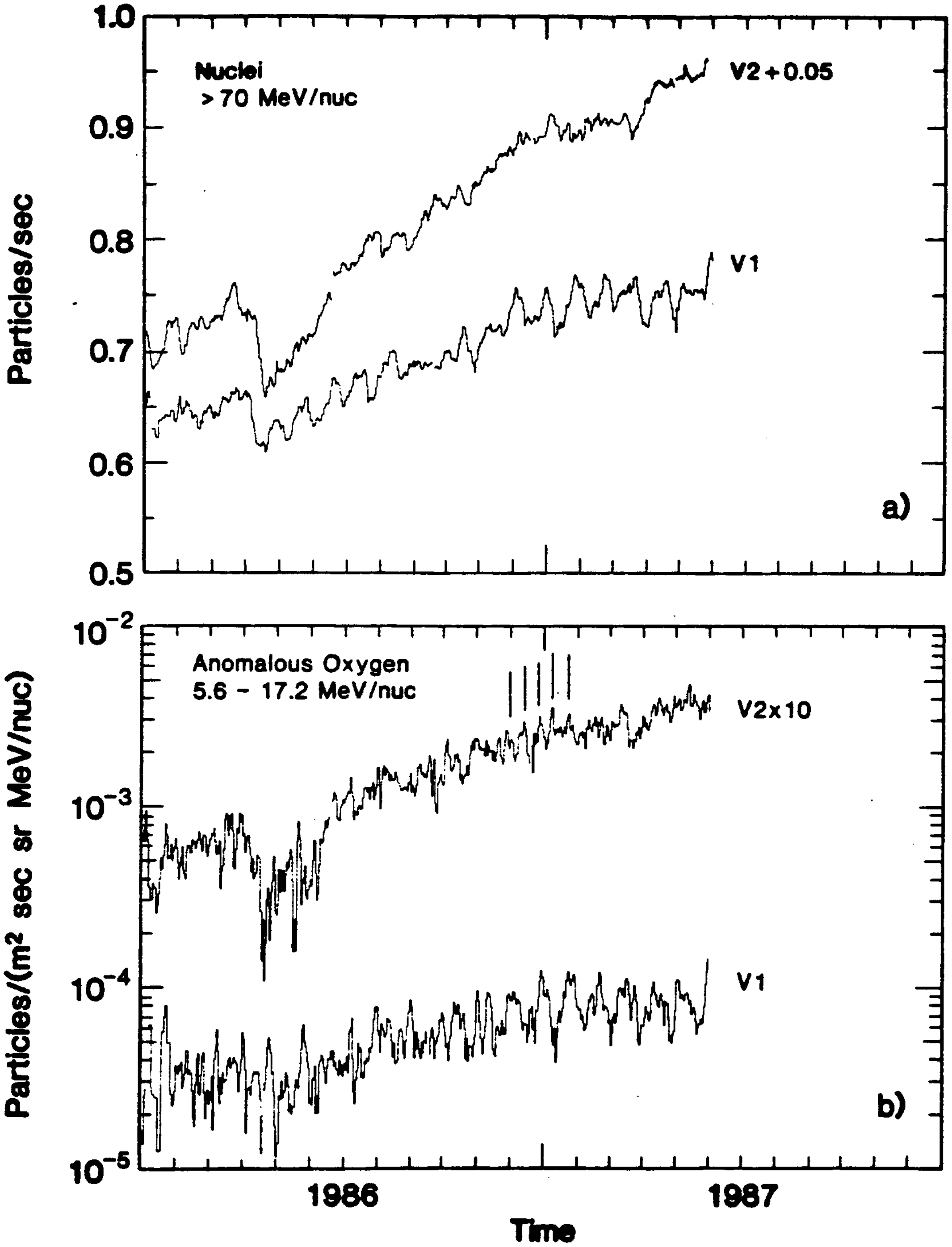

Figure 4

amplitude of the intensity variations, M_i, as the ratio of maximum to minimum fluxes observed on the ith spacecraft, then we have:

$$\frac{\ln(M_i)}{\Delta\Theta_i} = G_{\Theta_i} \tag{1}$$

where $\Delta\Theta_i$ is the maximum variation in magnetic latitude and G_{Θ_i} is the local latitudinal gradient. For the case of Voyager 1, which is at ~28° N latitude and hence expected to always be above the maximum excursion of the current sheet, $\Delta\Theta_1 = 2\alpha$.

For example, in early 1987 the Voyager 1 anomalous oxygen variations are observed to be a factor of $M_1 \approx 2$ in Figure 4b. Using the latitudinal gradient of -4.3%/deg from Figure 3b results in a current sheet tilt of ~8° to account for the amplitude of the Voyager 1 variations. If the gradient at Voyager 1 is larger, as illustrated by the dashed line in Figure 3b, a smaller current sheet tilt would be needed.

The situation is likely different for Voyager 2 which was at ~1.8° N latitude in early 1987, near the heliographic equator. Consider the case where the current sheet is centered on the spacecraft. The magnetic latitudes sampled by Voyager 2 would be in the range of $\pm\alpha$. Since drift theory would predict latitudinal gradients which are symmetric about the current sheet, $\Delta\Theta_2 = \alpha$ in Equation 1, resulting in a flux variation ratio $M_2 = \sqrt{M_1} \approx \sqrt{2}$ if the gradient is constant (i.e., if $G_{\Theta_1} = G_{\Theta_2}$).

The frequency is also different on Voyager 2 than on Voyager 1, since a maximum in intensity is reached each time the current sheet is crossed. In early 1987, five 13-day variations of approximately this magnitude are observed (see Figure 4b). If $G_{\Theta_2} < G_{\Theta_1}$, as illustrated by the dashed curve in Figure 3b, then even smaller variations in the Voyager 2 flux would be expected.

We also note that Equation 1 can be used to predict the relative local latitudinal gradients of two different particle populations. From Equation 2 the ratio of the logarithm of the amplitudes is proportional to the ratio of the latitudinal gradients. From Figures 4a and b we infer that in the vicinity of Voyager 1 the local latitudinal gradient of the anomalous oxygen is a factor of ~12 larger than that of nuclei with >70 MeV/nuc. This factor is somewhat larger than that reported for the large-scale latitudinal range 0-28° (~6 to 9), which may indicate that the latitudinal gradients of these two components have different latitudinal dependences.

In order to establish which of the two mechanisms discussed here are responsible for the latitudinal gradients of cosmic rays, it will be necessary to correlate plasma, magnetic field, and cosmic-ray data. If enhanced magnetic fields associated with merged interaction regions account for the variations, then the flux minima should be correlated with the current sheets which are embedded in such regions. On the other hand, if heliomagnetic latitude is the relevant organizing parameter, as suggested here, then current sheet crossings on Voyager 2 should be correlated with maxima in the cosmic-ray intensity.

1.2.3. 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.

Our work on solar flare, interplanetary, and galactic cosmic ray isotopes has resulted in the following recent talks and papers.

- "Solar Coronal Isotopic Abundances Derived from Solar Energetic Particle Measurements," Mewaldt, R. A. and E. C. Stone, *Bull. of Amer. Phys. Soc.* **32**, 1037 (1987).

- "Galactic Cosmic Ray Isotope Spectroscopy: Status and Future Prospects," Mewaldt, R. A., *Proceedings of the 13th Texas Symposium on Relativistic Astrophysics*, p. 573, World Scientific, Singapore (1987).

- "Isotope Abundances of Solar Coronal Material Derived from Solar Energetic Particle Measurements ," Mewaldt, R. A. and E. C. Stone, *Proceedings of the 20th International Cosmic Ray Conference, Moscow, USSR* **3**, 255 (1987).

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

The HNE is a joint experiment involving this group; M. H. Israel, J. Klarmann, and W. R. Binns (Washington University); and C. J. Waddington (University of Minnesota). HNE is designed to measure the elemental abundances of relativistic high-Z cosmic ray nuclei ($17 \leq Z \leq 130$). The results of such measurements are of significance to the studies of nucleosynthesis and stellar structures, the existence of extreme transuranic nuclei, the origin of cosmic rays, and the physical properties of the interstellar medium. HNE was successfully launched on HEAO-3 and operated until late May 1981.

The HEAO Heavy Nuclei Experiment Team has concentrated on understanding the unusual problem of unexpectedly good resolution in our charge spectrum at intermediate energies (~1.5 to 10 GeV/nucleon). We have qualitatively understood the problem in terms of the Cerenkov response function, in particular the contribution of delta-ray electrons to the production of Cerenkov light at higher energies. We have quantitatively demonstrated that the systematic error due to lack of calibration in this energy range is small compared to the statistical errors and are proceeding towards publication of this work.

We are also working toward publication with a study of the sidereal anisotropy of cosmic-ray Fe nuclei. We have derived an upper limit on the anisotropy for which we believe the systematic problems are significantly smaller than statistical errors. The data set selected for the anisotropy study also forms the basis for an effort to use vertical geomagnetic cutoff rigidities to determine the rigidity spectrum of cosmic-ray Fe in the 2 to 15 GV rigidity range.

Caltech has supported a study of the spectrum of silicon at energies above 50 GeV/nucleon which is being led by Washington University. This effort is inspired by the surprising spectral measurements reported by the Chicago CRN group. We have also supported the work done at the University of Minnesota on cross-sections measured in our 1986 Bevalac calibration.

The following talks and paper were presented during the reporting period:

- "The Energy Dependence of Fragmentation Cross-Sections of Relativistic Heavy Nuclei," Cummings, J. R. et al., *Bull. of Amer. Phys. Soc.* **32**, 1122 (1987).

- "Systematics of the Release of Residual Nuclei from Relativistic Nucleus-Nucleus Interactions," Waddington, C. J. et al., *Bull. of Amer. Phys. Soc.* **32**, 1122 (1987).

- "The Abundances of Ultraheavy Elements in the Cosmic Radiation: HEAO C-3 Results," Stone, E. C. et al., *Bull. of Amer. Phys. Soc.* **32**, 1067 (1987).

- "Cosmic Ray Energy Spectra between Ten and a Few Hundred GeV/amu for Elements between $_{18}$Ar and $_{28}$Ni," Israel, M. H. et al., *Bull. of Amer. Phys. Soc.* **32**, 1066 (1987).

- "Cosmic Ray Energy Spectra Between Ten and Several Hundred GeV/amu for Elements from $_{18}$Ar to $_{28}$Ni: Results from HEAO 3," Binns, W. R. et al., *Ap. J.* **324**, 1106 (1988).

- "Systematics of the Release of Residual Nuclei from Relativistic Nucleus-Nucleus Interactions," Binns, W. R. et al., *Physical Review C* (1987).

- "Response of Ionization Chambers and Cerenkov Counters to Relativistic Ultraheavy Nuclei," Klarmann, J. et al., *Proceedings of the 20th International Cosmic Ray Conference, Moscow, USSR* **2**, 390 (1987).

- "The Energy Dependence of Fragmentation Cross-Sections of Relativistic Heavy Nuclei," Waddington, C. J. et al., *Proceedings of the 20th International Cosmic Ray Conference, Moscow, USSR* **2**, 149 (1987).

- "Release of Nuclei from Relativistic Nucleus-Nucleus Interactions," Waddington, C. J. et al., *Proceedings of the 20th International Cosmic Ray Conference, Moscow, USSR* **2**, 152 (1987).

- "The Abundances of Ultraheavy Elements in the Cosmic Radiation," Stone, E. C. et al., *Proceedings of the 20th International Cosmic Ray Conference, Moscow, USSR* **1**, 366 (1987).

- "Anisotropy of Galactic Iron of Energy 30 to 500 GeV/amu Studied by HEAO-3," Garrard, T. L. et al., *Proceedings of the 20th International Cosmic Ray Conference, Moscow, USSR* **1**, 348 (1987).

- "Cosmic-Ray Energy Spectra Between Ten and Several Hundred GeV/amu for Elements from ${}_{18}$Ar to ${}_{28}$Ni--Results from HEAO-3," Israel, M. H. et al., *Proceedings of the 20th International Cosmic Ray Conference, Moscow, USSR* **1**, 330 (1987).

- "Energy Dependence of the Release of Nuclei from Relativistic Nucleus-Nucleus Interactions," Waddington, C. J. et al., *Bull. Amer. Phys. Soc.* **33**(4), 1060 (1988).

- "Charge Pickup by Relativistic Nuclei in Nuclear Interactions," , J. R. Cummings et al., *Bull. of Amer. Phys. Soc.* **33**(4), 1060 (1988).

1.2.5. Proposal for an Advanced Composition Explorer (ACE)

This investigation, submitted to NASA for the Explorer Concept Study Program, was proposed jointly by this group; R. E. Gold and S. M. Krimigis (APL/JHU); G. Geiss (University of Bern); J. A. Simpson and M. E. Wiedenbeck (University of Chicago); L. F. Burlaga and T. T. von Rosenvinge (GSFC); W. C. Feldman (LANL); G. Gloeckler and G. M. Mason (UMd); and D. Hovestadt (MPI). This Explorer-class mission would make comprehensive measurements of the elemental and isotopic composition of accelerated nuclei with increased sensitivity of several orders of magnitude, and with improved mass and charge resolution. ACE would 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 would 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 ($Z=40$), and element studies extending to U ($Z=92$).

ACE would be a coordinated experimental and theoretical effort, designed to investigate a wide range of fundamental problems. In particular, ACE would provide the first extensive tabulation of solar *isotopic* abundances based on direct sampling of solar material and would establish the pattern of *isotopic differences* between galactic cosmic ray and solar system matter. These composition data would be used to investigate basic dynamical processes that include the formation of the solar corona, the acceleration of the solar wind, and the acceleration and propagation of energetic nuclei on the Sun, in interplanetary space, and in cosmic ray sources. They would also be used to study the history of solar system material and of galactic cosmic ray material, and to investigate the differences in their origin and evolution.

The ACE study payload includes five 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 would play a leading role. These spectrometers would make use of the proven mass-resolution techniques and large-area detectors that were developed and tested by this laboratory over the past decade, partly through the support of this grant.

1.2.6. Galileo Heavy Ion Counter

This experiment, constructed by this group in collaboration with N. Gehrels at Goddard Space Flight Center, has been added to the Galileo mission as an engineering subsystem. 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" (SEU) in the attitude control system computer. (SEUs are state changes induced by ionizing radiation.) Caltech is responsible for management, detector testing, and calibration of the experiment, which is based on repackaging the Voyager CRS prototype unit (the PTM). Although the primary purpose is engineering support, the data will allow us to continue our investigation of spectra of trapped ions in the Jovian magnetosphere and their relation to the Jovian aurora. In addition, during cruise phase 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.

Current activities include response to new constraints due to mission redesign and attempting to maintain instrument reliability in the face of greatly extended ground handling. We have made preliminary plans for the mission operations and data analysis. We are also proposing to use some share of the very limited telemetry stream during the cruise phase inside 1 A.U. to monitor solar-flare induced SEUs. This period also represents a unique opportunity to measure the flux of the "anomalous" cosmic-ray component at solar distances of less than 1 A.U.

The Heavy Ion Counter (HIC) was re-installed on the spacecraft in April of 1988. In May, a presentation was made to the Science steering group to encourage the acquisition of HIC data in the early phases of the mission, inside of 1 A.U. from the Sun. A no-cost technique has been identified for acquiring this data, but no decision will be made before launch.

1.2.7. Astrophysics Data Program

One of us (RAM), in collaboration with W. R. Webber of the University of New Hampshire, has been awarded a guest-investigator grant under the Astrophysics Data Program to study "New Aspects of Heavy Cosmic Rays from Calcium to Nickel" using data from the HEAO-C-3 experiment. This investigation will apply newly measured cross sections and recent propagation models to the HEAO data set in an effort to search for evidence of cosmic ray re-acceleration in the interstellar medium.

2. Hard X-Ray and Gamma-Ray Astrophysics

This research program is directed toward the investigation of galactic, extragalactic, and solar hard X-rays and gamma rays with spectrometers of high angular resolution and moderate energy resolution carried on spacecraft and balloons. The main efforts have been directed toward the following two categories of experiments.

2.1. Activities in Support of or in Preparation for Spacecraft Experiments

These activities generally embrace prototypes of experiments on existing or future NASA spacecraft and they complement and/or support such experiments.

2.1.1. Gamma-Ray Imaging Payload (GRIP)

The GRIP instrument is a balloon-borne imaging γ-ray telescope for galactic and extra-galactic 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 had two successful flights from Alice Springs, Australia during the period covered by this status report. These followed two earlier flights from Palestine, Texas in October 1986, and Alice Springs in May 1987, bringing the total to four successful flights of the instrument in a 1-1/2 year time span.

The primary objective in the recent flights (November 1987 and April 1988) was the observation of SN 1987A in hard X-rays and γ-rays. A successful detection was made on each flight and preliminary results were reported in IAU circulars 4527 and 4584. Among the key features of the measurements were the first detection and measurement of scattered gamma-ray continuum above 500 keV and the first 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. 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. Results from the November 1987 flight have been reported in a paper presented at the Workshop on Nuclear Spectroscopy of Astrophysical Sources in December 1987.

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 and we are currently analyzing our data to refine the position determination of the source and to measure its spectrum.

A brief overview of the balloon flights may be useful. The November 1987 flight was a post-turnaround flight of rather short duration, approximately 7 hours of time at float. Unfortunately, a balloon defect was discovered during an initial launch attempt and this prevented a turnaround launch and consequently a longer flight. During recovery of the payload after the flight, significant damage to the instrument occurred, requiring extensive refurbishment between the November and April flights. In spite of these problems, the final outcome of the expedition was quite successful as it yielded the first detection by GRIP of SN 1987A.

As a result of analysis of the data from the November flight, we became concerned about possible geomagnetic anomalies in Australia on the order of 0.5 degrees in magnitude. We therefore implemented a dual CCD sun/star tracker. This performed successfully in the April flight and we now hope to define our aspect to better than 5 arc minutes accuracy. This will be quite important for the localization of the galactic center source as well as for elimination of contribution of nearby sources to the flux measurement of SN 1987A.

The April 1988 flight was the best flight of the GRIP instrument to date, being a true turnaround flight of 30 hours duration. The instrument performed very well, and the only disappointment was a tendency of the balloon to descend in the afternoon, resulting in a lower than optimal flight altitude for portions of the supernova observations. We had a rather good recovery of the instrument and suffered minimal damage of the payload. The major portions of the telescope are currently stored in Alice Springs, Australia to take advantage of possible future launch opportunities.

A report on the Texas flight is in the Moscow ICRC Proceedings:

- "First Flight of a New Balloon-Borne Gamma-Ray Imaging Telescope," Althouse, W. E. et al., *Proceedings of the 20th International Cosmic Ray Conference, Moscow, USSR* **1**, 84 (1987).

M. H. Finger completed a thesis on gamma-ray imaging:

- "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).

Other studies, including the observations of SN 1987A, have been reported as follows:

- "An Imaging Observation of SN 1987A at Gamma-Ray Energies," Cook, W. R. et al., *Submitted: Ap. J. (Letters)* (1988).
- "Gamma-Ray and Hard X-Ray Imaging of Solar Flares," Prince, T. A. et al., *Accepted for Publication in Solar Physics* (1988).
- "Imaging Observations of SN 1987A at Gamma-Ray Energies," Cook, W. R. et al., *Proceedings: Workshop on Nuclear Spectroscopy of Astrophysical Sources* (1987).

2.2. Experiments on NASA Spacecraft

Grant funds are used to provide a general support base and the facilities which make these programs possible.

2.2.1. Cygnus X-1 Rapid Timing Variability

We have a collaborative effort with the High-energy Astrophysics Group at JPL to investigate rapid timing variability in the gamma-ray source Cygnus X-1 using data from the SMM/HXRBS and HEAO-C1 instruments. Christopher Starr is being supported under the NASA Graduate Student Researchers Program to pursue this activity. Results will be discussed in later status reports.

3. Other Activities

R. A. Mewaldt is serving as a member of NASA's High Energy Astrophysics Management Operations Working Group (HEAMOWG) and the Cosmic Ray Program Working Group (CRPWG). He is also a member of the Superconducting Magnet Facility (Astromag) Definition Study Team, where he is chairman of the Science and Facility Subcommittee.

T. A. Prince has received a Presidential Young Investigator Award from the National Science Foundation and is serving as a member of the Gamma-Ray Astronomy Program Working Group (GRAPWOG) and the High-Energy Astrophysics Management and Operations working Group (HEAMOWG).

E. C. Stone continues to serve as NASA's Project Scientist for the Voyager Mission. He is also a member of the Commission on Physical Sciences, Mathematics, and Resources of the National Research Council and a member of the Committee on Space Policy of the National Academies of Science and Engineering.

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