NASA CR-177891

FINAL REPORT

For NASA Contract NAS5-25789

March 24, 1980 - December 31, 1984

REDUCTION AND ANALYSIS OF DATA FROM EXPERIMENT CAI ON THE IMP-8 MISSION

(NASA-CR-177891) REDUCTION AND ANALYSIS OF DATA FROM EXPERIMENT CAI ON THE IMP-8 MISSION Final Report, 24 Mar. 1980 - 31 Dec. 1984 (California Inst. of Tech.) 10 p
N86-32381
CSCL 03B G3/90
Unclas 43300

Prinicple Investigator: E. C. Stone
Co-Investigator: R. A. Mewaldt
California Institute of Technology
220-47 Downs Laboratory
Pasadena, CA 91125

The Electron/Isotope Spectrometer on IMP-8

The Caltech Electron/Isotope Spectrometer on IMP-8 has since 1973 been providing precise measurements of the energy spectra and time variations of low energy electrons (0.16 - 6 MeV), the isotopes of hydrogen and helium (~2 to 40 MeV/nucleon), and the elements from lithium through oxygen (~5 to 50 MeV/nucleon) in energetic particle fluxes of solar, galactic, interplanetary, and magnetospheric origin. We summarize here some of the many accomplishments that have resulted from EIS measurements during the period covered by this report, March 24, 1980 to December 31, 1984.

The Isotopic Composition of Galactic Cosmic Ray Hydrogen and Helium - In galactic cosmic rays (GCRs) the rare isotopes ^{2}H and ^{3}He are believed to be of secondary origin, and their abundance therefore provides information on the pathlength of cosmic ray ^{1}H and ^{4}He nuclei in the interstellar medium. The EIS provided significantly improved resolution of ^{2}H and ^{3}He (see, e.g., Fig. 1). Combining these measurements with improved interstellar propagation and solar modulation calculations, we found that the observed spectra of ^{2}H and ^{3}He could be accounted for by an interstellar pathlength of 7 ± 2 g/cm^{2}, consistent with that determined for heavier nuclei (see Fig. 2). We also concluded from the observed ^{2}H/^{3}He ratio that the interstellar energy spectra of ^{1}H and ^{4}He must be considerably steeper than the total energy power law often used in cosmic ray propagation and modulation studies.

Ever since 1973, when the "anomalous cosmic ray" (ACR) component of ^{4}He was discovered, we have used ^{3}He as a "tracer" to separate the ACR and galactic cosmic ray (GCR) contributions to the ^{4}He spectrum observed at 1 AU. In a recent survey of ~25 MeV/nucleon H and He isotope abundances from 1973 to 1979, we also found possible evidence for an "anomalous" contribution to the ^{1}H flux during 1976-1977, consistent with the predictions of one theoretical model.

Studies of the Anomalous Cosmic Rays - The energy region from ~1 to 30 MeV/nucleon includes nuclei accelerated in a variety of sources, including the anomalous cosmic ray component (see Fig. 3). In our 1974 report of a joint IMP-7/8 study of the elemental and isotopic composition of nuclei with $2 \leq Z \leq 8$, we found that the anomalous He, N, and O fluxes were predominately ^{4}He, ^{14}N, and ^{16}O, and that the energy spectra of Li, Be, B, and C showed no anomalous enhancements, but were consistent with solar modulation of the GCR component. Thus, there was no evidence for secondary fragmentation products arising from the enhanced N and O fluxes, and the ACR component must be a relatively pure sample of the source material. A recent paper based on IMP and ISEE-3 data extends these results with improved statistical accuracy.

EIS measurements were also the first to demonstrate significant time variations in the ACR fluxes, and to show that this component is more sensitive to solar modulation than galactic cosmic rays of similar energies. More recently, EIS observations have served as the 1 AU baseline in Pioneer/IMP studies of the radial gradient of ACR He and O, which resulted in gradients of 15±3% per AU for both species.

Observations of Hydrogen and Helium Isotopes in Solar Flares - In solar flares the rare isotopes ^{2}H, ^{3}H, and ^{3}He are produced by nuclear interactions of accelerated ^{1}H and ^{4}He

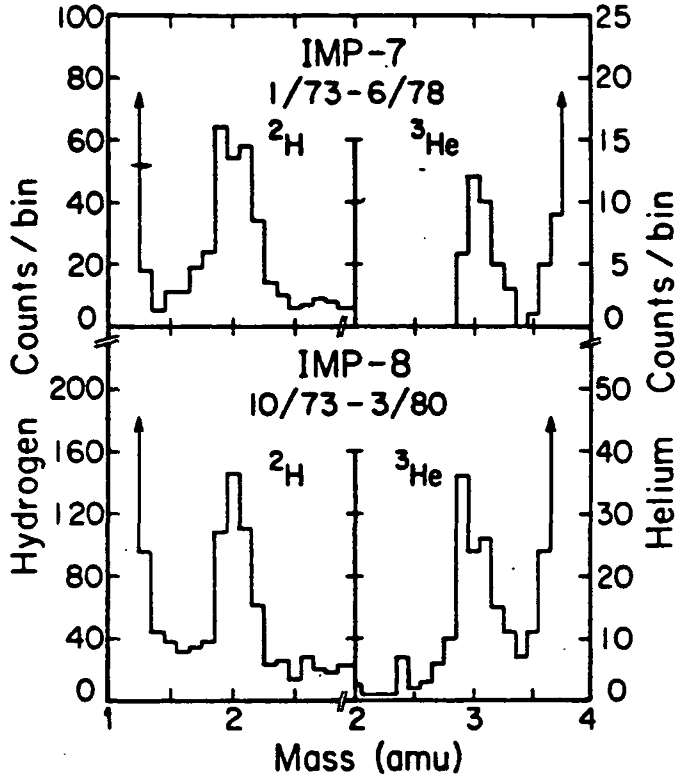

Figure 1: Examples of the mass resolution achieved for quiet-time ^{2}H and ^{3}He nuclei by the EIS instruments on IMP-7 and IMP-8.

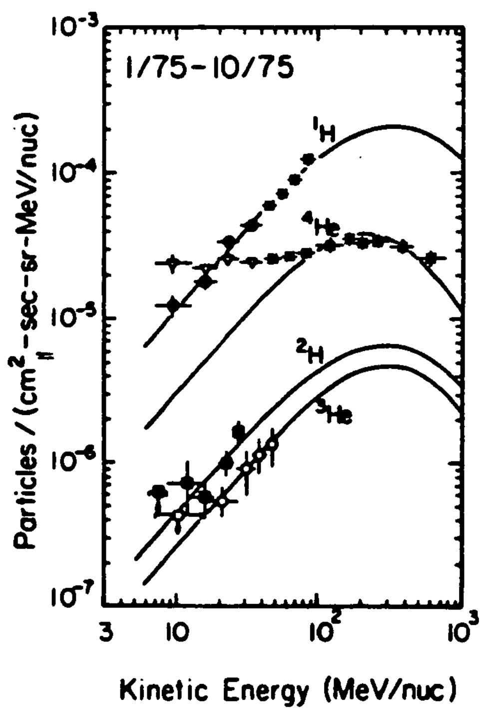

Figure 2: An example of measured and calculated energy spectra for the quartet of H and He isotopes.

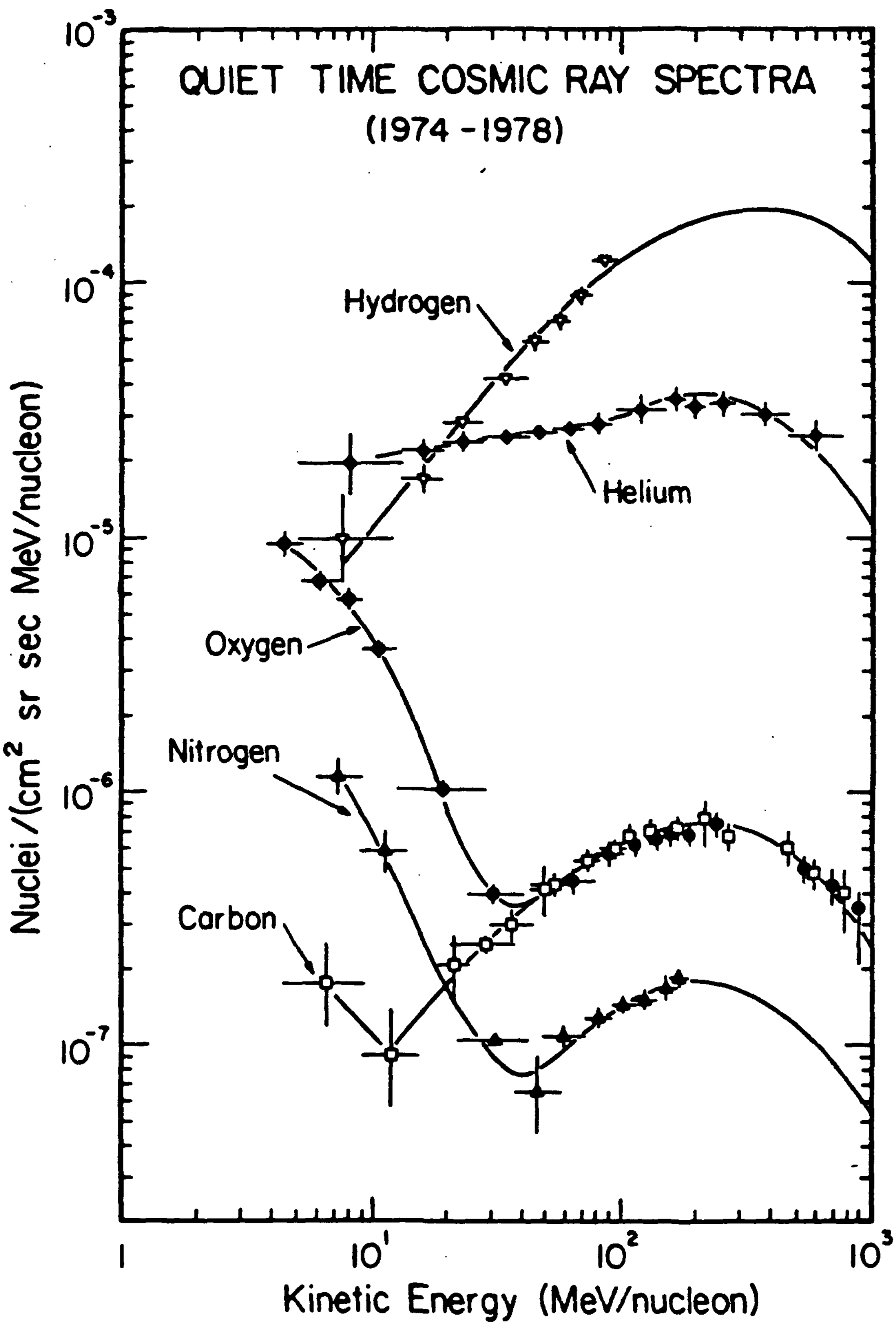

Figure 3: Quiet-time energy spectra observed by IMP-8 for the elements H, He, C, N, and O. Note the "anomalous enhancements in the spectra of He, N, and O. Data points at energies greater than ~50 MeV/nucleon are from the University of Chicago experiment on IMP-8.

nuclei as they pass through the solar atmosphere. In addition, the abundance of ^{3}He is sometimes enhanced by orders of magnitude (^{3}He/^{4}He $\geq$ 0.1) in so-called ^{3}He-rich flares. Using EIS data from 1973-1974 we placed new limits on the abundance of ^{2}H and ^{3}H in large solar events, and identified a number of ^{3}He-rich flares without corresponding increases in ^{2}H or ^{3}H, thereby providing further evidence that such events cannot be explained by nuclear interaction models. We also discovered that ^{3}He-rich events typically contain enrichments of heavy nuclei ($Z \geq 6$), thereby providing an additional constraint on theoretical models for these events.

Recently we extended our search for these rare isotopes to higher energies and to additional flares observed from 1974 to 1979. Figure 4 shows examples of the mass spectra, which indicate no evidence for a finite abundance of ^{2}H or ^{3}H. The resulting upper limits for the ^{2}H/^{1}H and ^{3}H/^{1}H ratios are up to an order of magnitude lower than finite measurements reported earlier by another group at the same energy/nucleon. These results show that (contrary to earlier reports) the typical solar flare particle escaping from the sun has not passed through any significant amount of material (< 30 mg/cm^2), a result consistent with recent solar γ-ray observations.

Electron and Positron Measurements - The EIS instruments provided the first high-resolution low-background observations of interplanetary electrons with energies near ~1 MeV, due in part to the built-in analysis mode for monitoring γ-ray and neutron-induced background. Thus, EIS observations showed that the spectrum of quiet-time electrons from ~0.2 to 3 MeV was a factor of 10 to 20 lower than previously thought. In addition, the EIS instruments extended the energy spectrum of Jovian electrons observed at 1 AU during so-called "quiet-time increases" to lower energies, and showed that Jovian electrons dominate the flux of quiet-time electrons at 1 AU throughout the year, and not just at the time of nominal field-line connection to Jupiter.

The first measurements of solar flare electron spectra over a broad energy interval, extending from ~20 keV to ~20 MeV, resulted from a collaborative study (with UC Berkeley and Goddard) based on observations from five separate instruments on IMP 6, 7, and 8. It was discovered that each of nine events studied had the same spectral shape - a double power law with a smooth transition at ~100-200 keV, with power law exponents of 0.6-2.0 below and 2.4-4.3 above (see, e.g., Figure 5). Based on interplanetary propagation studies, and hard x-ray and microwave observations, it was concluded that the observed spectral shape was representative of that for electrons escaping from the Sun, and probably characteristic of the accelerated spectra *on* the Sun.

At energies from ~0.16 to 1.6 MeV the EIS instruments can separate positrons from electrons, as shown during extensive pre-launch calibrations. Simultaneous IMP-7 and IMP-8 observations demonstrated that the flux of ~1 MeV positrons is at least a factor of 10 lower than reported by OGO-3 observers, with no evidence for low-energy positrons that might come from supernovae or radioactive β-decay. We also reported upper limits to the positron fraction in large solar flares and in small ^{3}He-rich flares.

Studies of Interplanetary Recurrent Events - During periods between impulsive solar particle events the interplanetary particle fluxes at < 10 MeV/nucleon are often dominated by recurrent events (also called "corotating" events) which recur at Earth at ~27 day intervals. Soon after Pioneer observations showed that particles in these

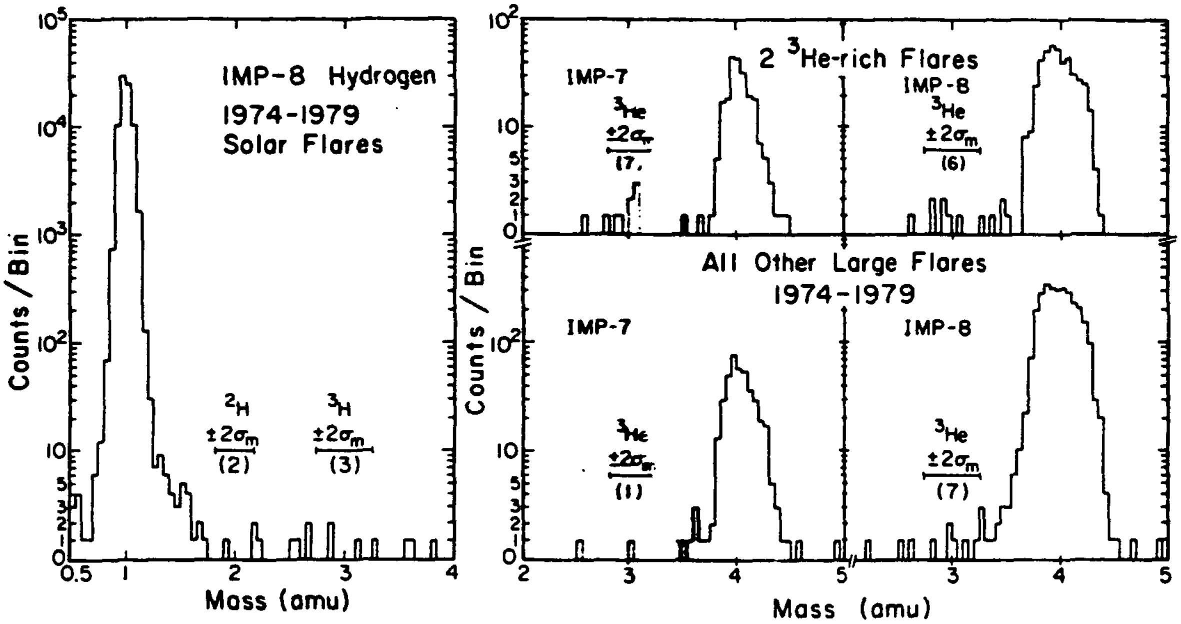

Figure 4: Mass histograms of H and He isotopes obtained from a sum of large flares observed from 1974 to 1979. There is no evidence for ^{2}H, ^{3}H, or ^{3}He above the background level. A small amount of ^{3}He was observed in the two ^{3}He-rich flares.

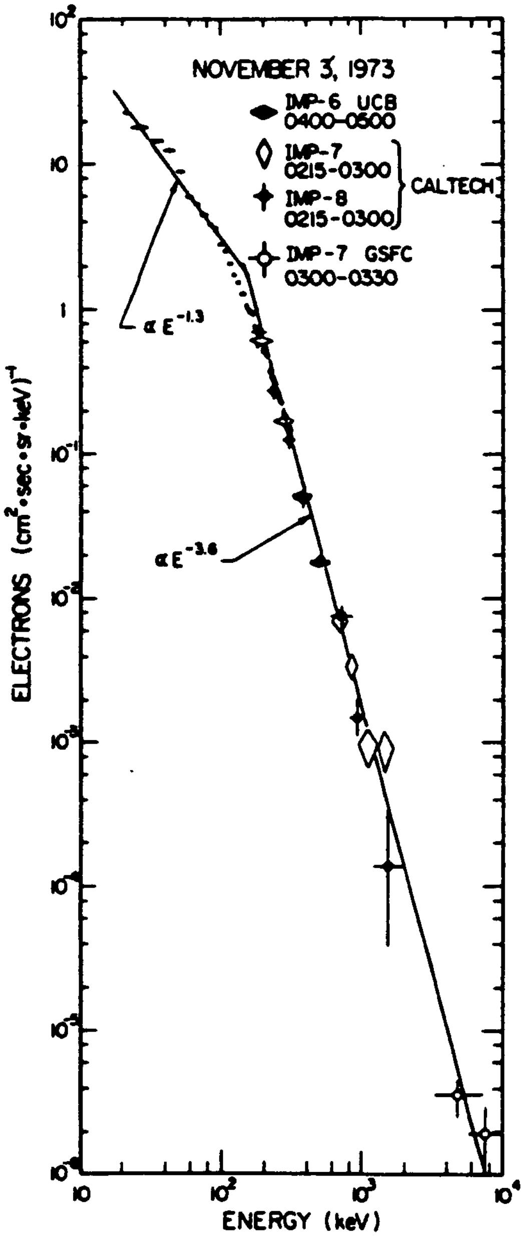

Figure 5: An example of high-resolution energy spectra for solar flare electrons obtained for the Nov. 3, 1973 event. The EIS data extend from 0.2 to 2 MeV. Note the excellent agreement between the various sensors.

events are accelerated in interplanetary space, and not on the Sun, an extensive EIS study of the particle anisotropy in recurrent events was completed. This study discovered that the diffusive streaming of ~2 MeV protons was *towards* the Sun, with a mean radial component of ~14%, indicating a positive radial gradient with a source of particles beyond 1 AU and a sink inside. In one of several subsequent studies we used simultaneous measurements of the radial gradient and the anisotropy of particles in several individual recurrent events to provide a direct estimate of the radial diffusion coefficient of ~1.6 MeV protons in interplanetary space. The value obtained (3 to 9 x 10^{20} cm^2/sec) is consistent with the results of solar flare propagation studies, but uses a new and independent method and applies to somewhat different conditions.

The Magnetopause Energetic Electron Layer - A layer of energetic (>200 keV) electrons was discovered with the EIS on IMP-8. The layer encircles the entire magnetotail and varies in thickness from ~1 R_E to ≥5 R_E, depending on geomagnetic activity. The tailward energy flow of energetic electrons in the layer varies from ~10^{14} ergs/s to 10^{15} ergs/s with increasing geomagnetic activity. It was shown that this energy flow is regulated by the incident solar wind, and comparison with plasma measurements suggests that the flow may extend to much lower energies and much larger fluxes, corresponding to a total energy flow of 10^{18} to 10^{19} ergs/s.

Bursts of energetic electrons were also observed in front of the bowshock streaming toward the sun along interplanetary magnetic field lines that trace to the inner magnetosheath. The total energy flow of >200 keV electrons averages ~2 x 10^{14} ergs/s, comparable to the tailward flow of electrons in the magnetopause electron layer. Studies suggest that the upstream electrons and those in the magnetopause electron layer are closely related and probably have a common origin in the inner magnetosheath or possibly in the magnetosphere.

Substorm Associated Streaming Energetic Electrons - In the magnetotail the occurrence of streaming energetic electrons is an indication that the spacecraft is likely on an open magnetic field line. It was discovered that the occurrence of such streaming is associated with a southward magnetic field as might be expected if the open field line resulted from magnetic reconnection. The streaming events and southward fields were also associated with the onset of substorms as indicated by rapid increase in the AE index.

Subsequent studies of the LASL plasma data during these events provided further evidence for substorm-associated reconnection in the magnetotail plasma sheet by showing that the streaming electrons are characteristically preceded by a ~15 minute period of tailward plasma flow and are followed by a dropout of the plasma sheet, both being classical signatures of magnetic reconnection and plasmoid formation.

In five of the reconnection events a pulse of heated plasma electrons appeared at the time of strongest southward magnetic fields just before the plasma sheet dropout. The hot plasma was Maxwellian with a spectral bump in the tail of the electron distribution function that could be the remnant of a 2 to 5-kV beam which produced the heating. These new features of the microstructure of magnetic reconnection are outside the scope of standard MHD models and resemble some of the features observed in laboratory reconnection events.

BIBLIOGRAPHY

"Streaming Energetic Electrons in Earth's Magnetotail: Evidence for Substorm-Associated Magnetic Reconnection", J. W. Bieber and E. C. Stone, Geophys. Res. Ltrs. 7, 945 (1980).

"The Isotopic Composition of Cosmic Ray Carbon, Nitrogen, and Oxygen Nuclei", R. A. Mewaldt, J.D. Spalding, E. C. Stone and R. E. Vogt, Bull. Am. Phys. Soc. 25, 546 (1980).

"Open Field Lines in the Magnetotail and Their Relationship to Geomagnetic Activity", J. W. Bieber and E. C. Stone, EOS Trans. AGU 61, 344 (1980).

"Energetic Electrons Upstream of the Bow Shock and in the Magnetosheath", J. W. Bieber and E. C. Stone, Upstream Wave and Particle Workshop, JPL, April, 1980.

"Two-Spacecraft Observations of Energetic Electrons in Earth's Magnetotail", J. W. Bieber and E. C. Stone, ISEE Geomagnetic Tail Workshop, Seattle, March, 1981.

"A Two-Spacecraft Study of Substorm-Related Streaming Energetic Electrons", J. W. Bieber, and E. C. Stone, EOS Trans. AGU 62, 369 (1981).

"The Isotopic Composition of Low Energy Cosmic Rays", R. A. Mewaldt, J. D. Spalding, E. C. Stone, and R. E. Vogt, 17th Int'l. Cosmic Ray Conference, Paris, France, Conf. Papers 2, 68 (1981) and 11, 431 (1981).

"The Energy Spectrum of 20 keV - 20 MeV Electrons Accelerated in Large Solar Flares", R. P. Lin, R. A. Mewaldt, and M. A. I. Van Hollebeke, 17th Int'l. Cosmic Ray Conference, Paris, France, Conf. Papers 3, 64 (1981).

"A Study of Temporal and Radial Dependencies of the Anomalous Helium and Oxygen Nuclei", W. R. Webber, F. B. McDonald, T. T. von Rosenvinge, and R. A. Mewaldt, 17th Int'l. Cosmic Ray Conference, Paris, France, Conf. Papers 10, 92 (1981).

"Plasma Behavior During Energetic Electron Streaming Events: Further Evidence for the Substorm-Associated Magnetic Reconnection", J. W. Bieber, E. C. Stone, E. W. Hones, Jr., D. N. Baker, and S. J. Bame, EOS Trans. AGU 62, 986 (1981).

"Energetic Electrons in the Magnetosheath and Upstream of the Bow Shock", J. W. Bieber, and E. C. Stone, J. Geophys. Res. 87, 85 (1982).

"The Energy Spectrum of 20 keV - 20 MeV Electrons Accelerated in Large Solar Flares", R. P. Lin, R. A. Mewaldt, and M.A.I. Van Hollebeke, Ap.J. 253, 949 (1982).

"Observations of Substorm-Associated Magnetic Reconnection", J. W. Bieber, E. C. Stone, E. W. Hones, Jr., D. N. Baker, and S. J. Bame, presented at 1982 Yosemite Conference on Origins of Plasmas and Electric Fields in the Magnetosphere, January, 1982.

"Reconnection - Associated Energization of Plasma Sheet Electrons", J. W. Bieber, E. C. Stone, E. W. Hones, Jr., D. N. Baker, S. J. Bame, and R. P. Lepping, EOS Trans. AGU 63, 418 (1982).

"Plasma Behavior During Energetic Electron Streaming Events: Further Evidence for Substorm-Associated Magnetic Reconnection", J. W. Bieber, E. C. Stone, E. W. Hones, Jr., D. N. Baker, and S. J. Bame, Geophys. Res. Ltrs. 9, 664 (1982).

"Microstructure of Magnetic Reconnection in Earth's Magnetotail", J. W. Bieber, E. C. Stone, E. W. Hones, Jr., D. N. Baker, S. J. Bame, and R. P. Lepping, J. Geophys. Res. 89, 6705 (1984).

"A Search for Deuterium, Tritium and ^{3}He in Large Solar Flares", R. A. Mewaldt and E. C. Stone, Bull. Am. Phys. Soc., 28, 742 (1983).

"Cosmic Ray ^{2}H, ^{3}He, and Anomalous H and He Nuclei", E. C. Stone and R. A. Mewaldt, ibid.

"A Search for ^{2}H, ^{3}H, and ^{3}He in Large Solar Flares", R. A. Mewaldt and E. C. Stone, 18th International Cosmic Ray Conference, Bangalore, India, Conf. Papers, 4, 52 (1983).

"Deuterium, ^{3}He, and Anomalous H and He Nuclei", R. A. Mewaldt and E. C. Stone, ibid 2, 42 (1983).

"A Search for ^{2}H, ^{3}H, and ^{3}He in Large Solar Flares", R. A. Mewaldt and E. C. Stone, EOS Trans. AGU, 45, 791 (1983).

"The Isotopic Composition of the Anomalous Low-Energy Cosmic Rays", R. A. Mewaldt, J. D. Spalding, and E. C. Stone, Ap.J. 283, 450 (1984).