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EXPERIMENT FOR HIGH ENERGY, HEAVY NUCLEI COMPOSITION (ONR-604)

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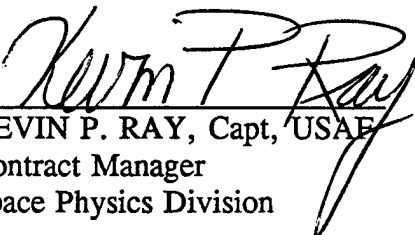
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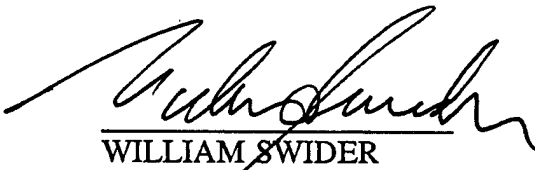
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A model of the Interplanetary Heavy Ion Environment which included both galactic cosmic rays (GCR) and solar energetic particles (SEP), was developed for the CRRES mission. The model was based on data from the ONR-604 experiment which flew on CRRES. A description of the datasets, analysis software, and cosmic ray model is given, as well as a description of the validation of the model.

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EXPERIMENT FOR HIGH ENERGY, HEAVY NUCLEI COMPOSITION (ONR-604)

1. INTRODUCTION

This grant has provided support for research at the Laboratory for Astrophysics and Space Research of the University of Chicago during the period May 1990 - March 1994, using the data returned by the University of Chicago ONR-604 experiment on the CRRES Mission.

The main stages of this work have been:

1) Development of the software necessary for data processing and analysis. Data processing;

2) Creation, in collaboration with the groups at Louisiana State University (LSU) and the Lockheed Palo Alto Research Laboratory (LPARL) of the Lockheed Co., of a Cosmic Ray Model ("CRRES/SPACERAD Heavy Ion Model of the Environment", [CHIME]) to predict at a given time the intensity of energetic heavy particles in the near Earth's space;

3) Investigation in specific areas of the scientific objectives proposed for the ONR-604 experiment based on measurements of fluxes, elemental and isotopic composition of high energy, heavy particles.

During the period April 1, 1991 to November 19, 1991 all work related to ONR-604 data ceased at this Laboratory in accordance with the limitation of funds clause.

2. SOFTWARE DEVELOPMENT AND DATA PROCESSING

1) Launch Support.

The launch support consisted in:

a) Debugging of the CRRES SpiderBox/ONR-604 ground support equipment (GSE) system;

b) Support of CRRES launch operations, and;

c) Analysis of the immediate post-launch flight data through the ONR-604 Ground Support Equipment.

2) Development of the Datasets and Software Required for Analysis of the ONR-604 Data

Steps in this work were:

a) Specification and debugging of the ONR-604 AFGL Agency Tape;

b) Design, coding, and debugging of the 8 major computer programs to produce the analysis tapes, and the counting-rate and parameter plots.

The Data Processing and Analysis System resulted in over 20,000 lines of 'C', Fortran, and Unix Shellscript code. This System lived in an environment consisting of a Sun SparcServer 390, a Sun SparcStation 330, 3 Sun SparcStation-1s and 15 Macintosh workstations. These machines were all tied together and to the internet universe by ethernet and/or appletalk networks;

c) Documentation of the programs, shellscripts, operation procedures, and formats. The primary document entitled "CRRES Data Processing & Analysis" was subsequently distributed to AFGL, all ONR-604 co-investigators and collaborators, the researchers and operations staff at the University of Chicago;

d) Implementation and subsequent operation of the above Data Processing and Analysis System to create the second-generation of analysis datasets on magnetic tapes and exabyte cartridges.

FIGURE 1 shows the data processing flow, the used programs, and the inputs and outputs in every processing step.

Brief description of the major programs:

ADO.	Copies AFGL agency tapes to disk, where all of an orbit's 5 files can be accessed concurrently to permit merging. Establishes table of recommended starts and ends to eliminate overlap.
PHATER.	Merges all 5 types of data for an orbit together. Eliminates overlap. Verifies accuracy of Universal Time assignment. Assigns UT of collection to pulse-heights and rates. Calculates position, velocity, B, L, B-experimental (from magnetometer data) and attitude. Produces 8 logs sorted by orbit and 1 log sorted by processing order.
PHNXCAL.	Processes in-flight-calibrator runs which occur once per week. Produces gains, offsets, and deviations from linearity for all 28 amplifiers.
C2E.	Converts PHA from channel number to energy. Calculates each particle trajectory. Approximates the atomic charge of each particle.
PARAM.	Calculate floating point averages for the 43 rates, B, L, B-experimental, satellite radial distance from earth, and other parameters.
PIMPLOT.	Produces plots of PARAM parameters on the Laserwriter.
COALLISTSP.	Lists any arbitrary items from PHRATER output tape or C2E tape in a special binary format that the Macintosh program IGOR can use.
SUMSTAT.	Sums together selected flux statistics produced by COALLISTSP

CRRES ONR-604 Data Processing and Analysis System
at the Laboratory for Astrophysics and Space Research
of the University of Chicago's Enrico Fermi Institute

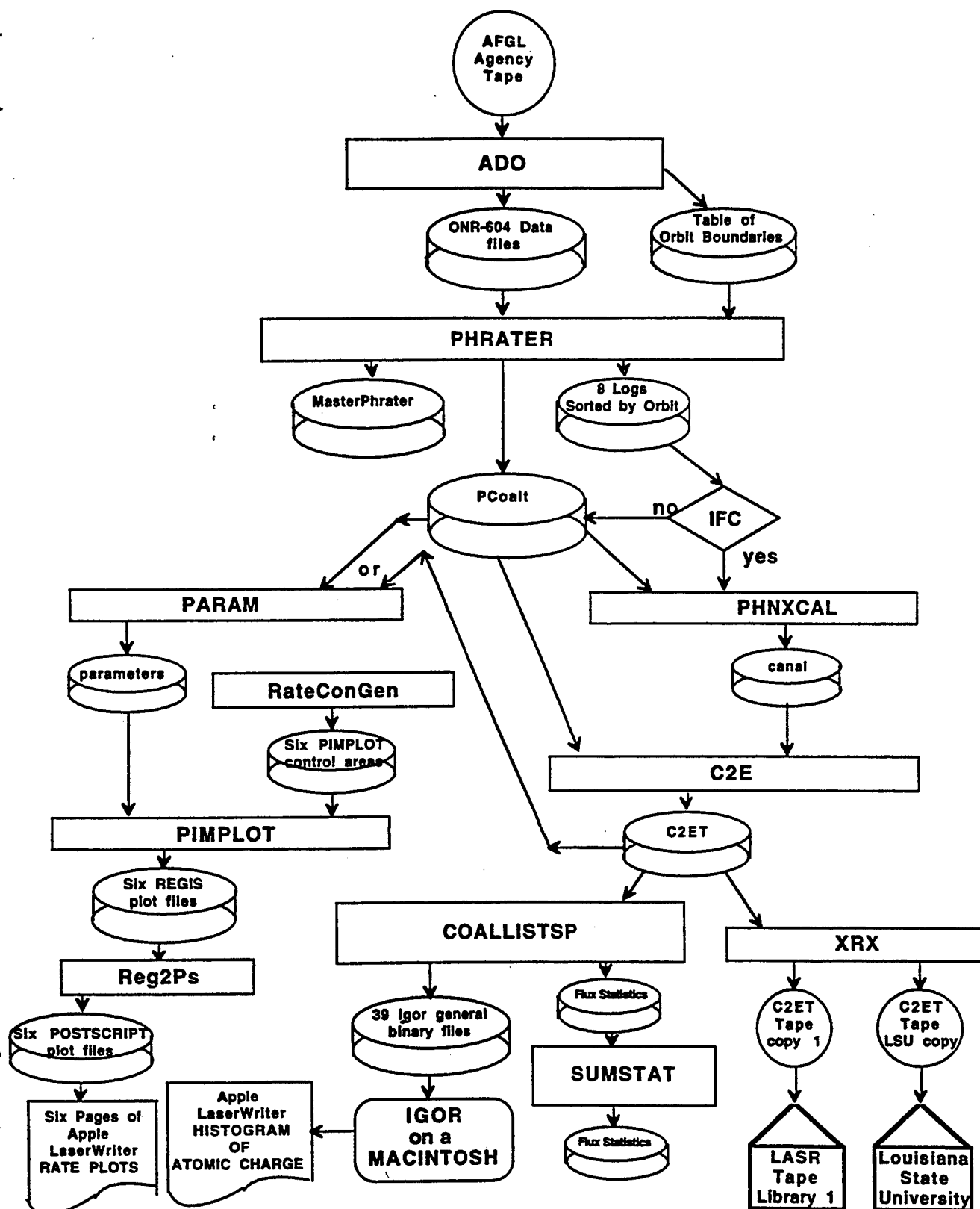Figure 1

3. Data Processing.

All the AFGL agency tapes were processed. This resulted in 212 reduced C2E tapes of which copies were sent to the collaborators of the University of the Chicago in Louisiana State University.

FIGURE 2 shows the distribution of data processing tasks between the University of Chicago, LSU and LPARL. The processing includes also the merging of additional data from the University of Chicago neutron monitors and from the University of Chicago experiment on the satellite IMP-8 in orbit in the near Earth space outside the Earth's magnetosphere. In particular the IMP data has been a very valuable support and complement in the scientific studies with ONR-604 data.

It can be seen that the data analysis results in the construction of the "CRRES/SPACERAD Heavy Ion Model of the Environment" (CHIME).

3. THE COSMIC RAY MODEL *(Papers 5, 6, 7, 8 in the Appendix)*

1. The CHIME Model.

A primary objective of the University of Chicago ONR-604 experiment has been the construction of a <u>Cosmic Ray Model</u> that can predict the intensity of energetic heavy ions in the near Earth's space at a given time. This prediction can be used to asses the damage (e. g. single event upsets, SEU) that such ions can inflict to the microelectronics at the hearth of space vehicles.

The heavy ion energetic (> 10 MeV/nucleon) particle population in the vicinity of the Earth is dominated by three components:

a) Solar energetic particles (SEP), which are associated with solar flare eruptions. This component was particularly important during the CRRES mission which occurred at times of maximum solar activity;

b) Galactic cosmic rays (GCR), which originate outside the heliosphere;

c) The anomalous components (AC), which have been measured in a few elements (He, N, O, Ne) and are only present at low energies (< 60 MeV/nucleon). In the interplanetary space near Earth these components are only significant at times of low level of solar modulation.

To predict the absolute abundance spectrum of the particle population in the Earth's vicinity our group at the University of Chicago, together with groups at Louisiana State University, and the Lockheed Co. has developed a model based on our current understanding of GCR, SEP and AC astrophysics. This model has been designated CHIME (for "CRRES/SPACERAD Heavy Ion Model of the Environment").

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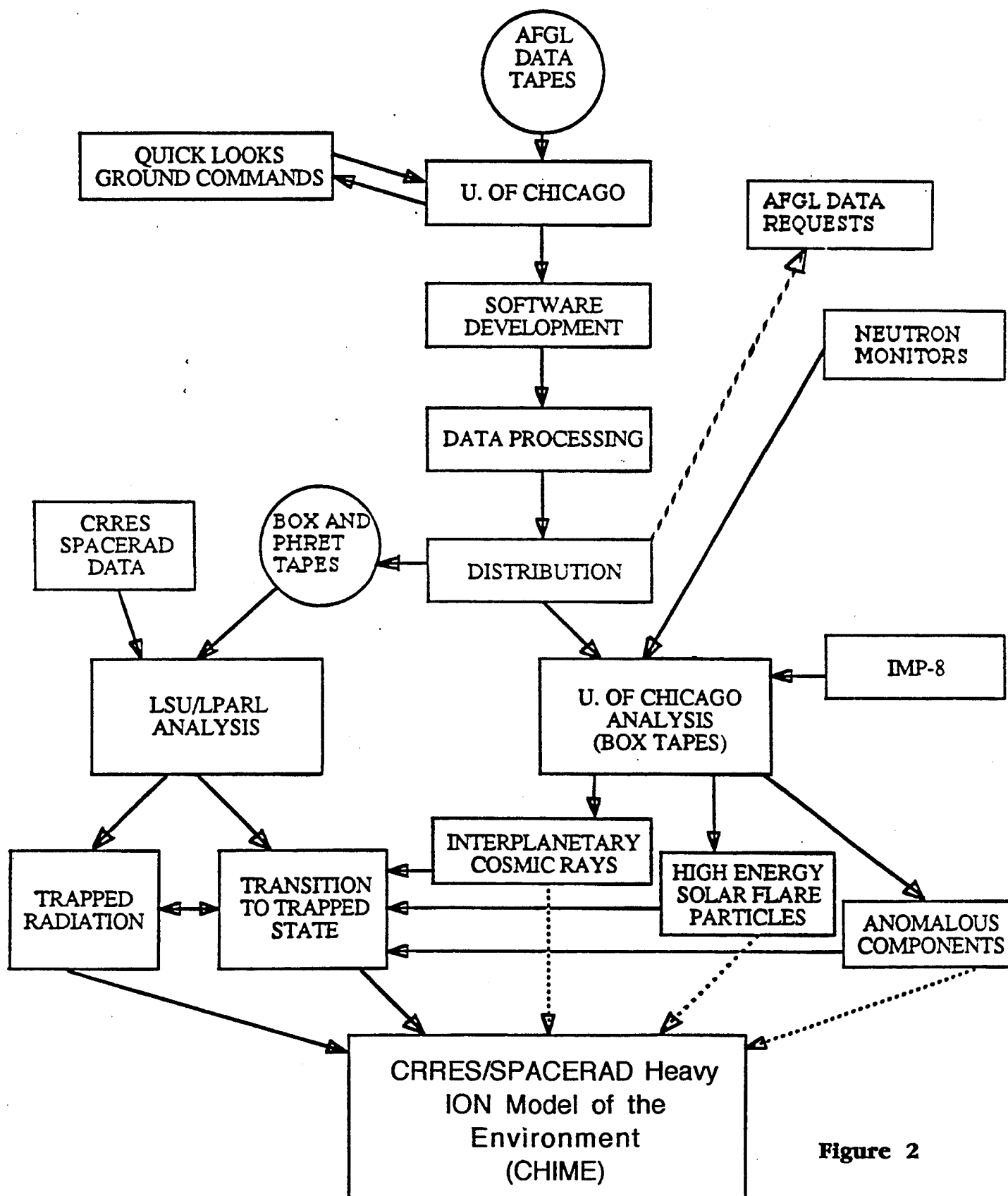# ONR-604 DATA PROCESSING AND ANALYSIS

Figure 2

The model includes the SEP maximum fluence, time dependent behavior, heavy ion content, and energy spectrum. For the GCR it starts from the assumption of a cosmic ray source composition, then follows the evolution of the cosmic ray composition during interstellar transport and partial leakage from the Galaxy until arrival to the local interstellar space. The modifications due to solar modulation are taken into account through the values of the force-field parameter Φ. For the AC, differential energy spectra (assumed to originate at the edge of the heliosphere) have been deduced from measurements at 1 AU and other radial distances from the Sun, and the spectra at Earth calculated using the parameter Φ.

CHIME predicts the energy spectra of all stable and long-lived species, from ^{1}H to ^{58}Ni over an energy range from 10 to 50,000 MeV/nucleon.

2. Validation of the CHIME Model.

The Cosmic Ray Model has been based in previous energetic particle measurements over many years, at different radial distances from the Sun and based on a growing understanding of the nature and dynamics of solar energetic particles, galactic cosmic rays and anomalous components. An outstanding part of this data base originated in the past from measurements carried out by University of Chicago satellites in the IMP missions and in the Pioneer probes.
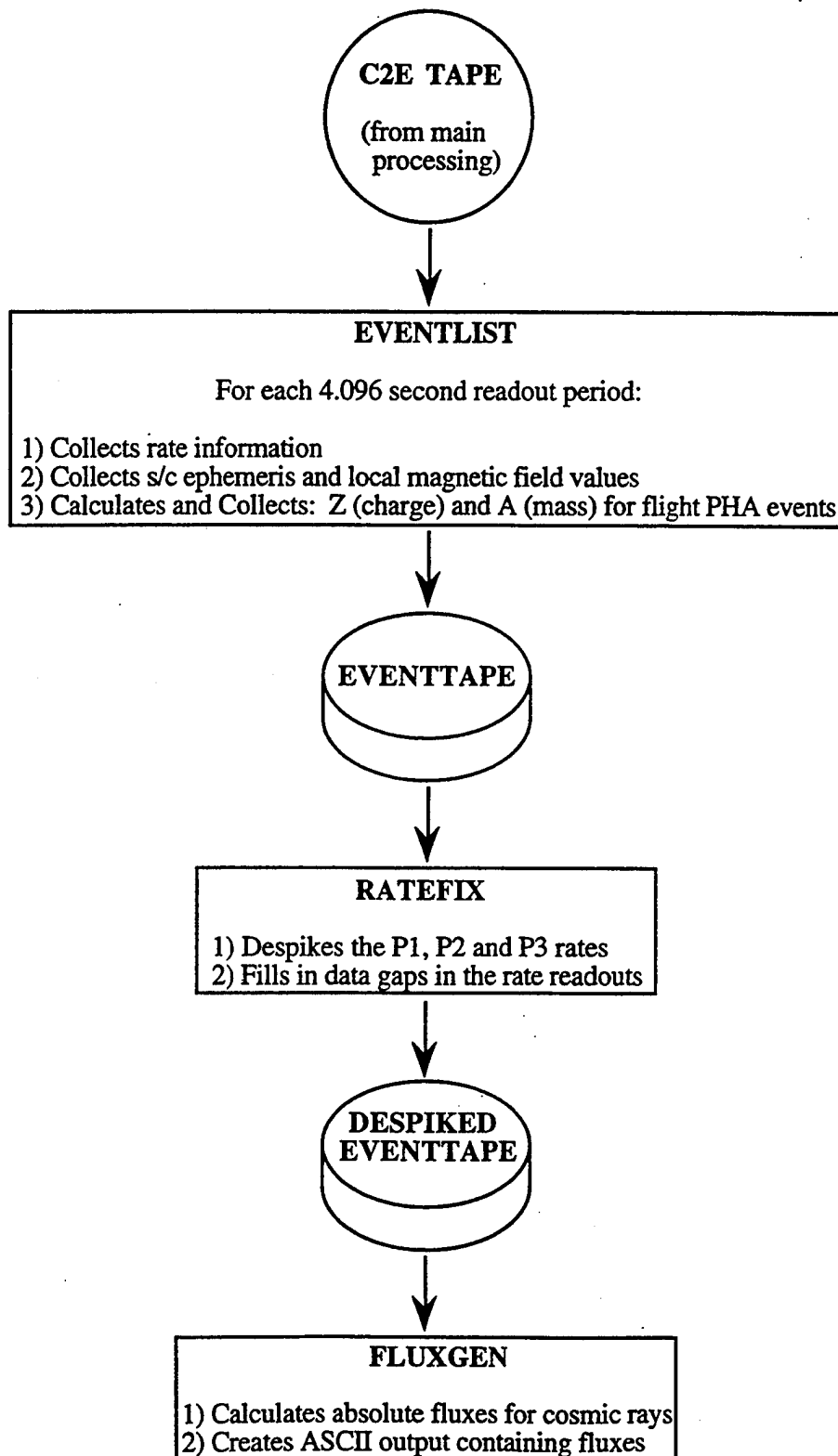
For a validation of the model and a final adjustment of its parameters we used data from the CRRES ONR-604 instrument taken inside the Earth's magnetosphere and complemented by data taken near Earth outside the magnetosphere by the University of Chicago experiment on the IMP-8 satellite. A first step has been to determine the correctness of the fluxes calculated using the ONR-604 data taken beyond L > 4.75 by comparing them with IMP-8 fluxes.

FIGURE 3 shows a flowchart describing the computer calculation of fluxes using ONR-604 data. The first step in the flux calculation is the identification of the charge and mass for pulse-height analyzed (PHA) events identified by the Chicago experiment. The program EVENTLIST takes the production C2E Tapes and determines which PHA events will be used in the later flux calculations. Events are discarded immediately from the flux analysis if the fail one of three tests for consistency. Events must

a) have single tracks in the detectors (no multiple coincidences are studied),

b) have straight line paths through the telescope as determined by the six position sensing detectors (PSD) at the top of the detector stack, and

c) stop in one of the eight large silicon detectors (Kevexes) at the bottom of the detector stack.

If an event meets all three of the above criteria its charge and mass are calculated. The method of calculation is a energy loss (dE/dx) in one set of detectors (consisting of one or more detectors) versus residual energy loss (E) in another set. If a particle stops in the 1st Kevex only a single charge and mass are determined. If the particle stops in the 2nd through 8th Kevex multiple determinations of charge and mass are made. When a particle has multiple determinations of charge all the calculations of charge must agree to within one charge unit or the particle is discarded from further analysis.

Flow Chart for the Flux Calculations
used in the validation of the CHIME model

```
          ┌─────────────┐
          │  C2E  TAPE  │
          │             │
          │ (from main  │
          │ processing) │
          └──────┬──────┘
                 │
                 ▼
┌────────────────────────────────────────────────────┐
│                    EVENTLIST                         │
│                                                      │
│     For each 4.096 second readout period:            │
│                                                      │
│  1) Collects rate information                        │
│  2) Collects s/c ephemeris and local magnetic field  │
│     values                                           │
│  3) Calculates and Collects:  Z (charge) and A (mass)│
│     for flight PHA events                            │
└───────────────────────┬──────────────────────────────┘
                        │
                        ▼
                  ╭───────────╮
                  │ EVENTTAPE │
                  ╰───────────╯
                        │
                        ▼
        ┌───────────────────────────────────┐
        │             RATEFIX               │
        │                                   │
        │  1) Despikes the P1, P2 and P3    │
        │     rates                         │
        │  2) Fills in data gaps in the     │
        │     rate readouts                 │
        └─────────────────┬─────────────────┘
                          │
                          ▼
                    ╭──────────╮
                    │ DESPIKED │
                    │ EVENTTAPE│
                    ╰──────────╯
                          │
                          ▼
        ┌───────────────────────────────────┐
        │            FLUXGEN                │
        │                                   │
        │ 1) Calculates absolute fluxes for │
        │    cosmic rays                    │
        │ 2) Creates ASCII output           │
        │    containing fluxes              │
        └───────────────────────────────────┘
```

Figure 3

The next step in the flux calculation is to collect all the good PHA events in time order. Each event is associated with a particular 4.096 second readout period. Each readout period contains rate information in addition to eight possible PHA events. During each readout period an average for the spacecraft ephemeris and magnetic field information are also collected. All of the rate information, spacecraft information and good PHA events are recorded in a condensed data set for further analysis.

At this point the three rate readouts, P1 rate, P2 rate and P3 rate, are processed through a comprehensive rate despiker and interpolator, RATEFIX. All spurious rate readouts are eliminated. Periods which contain pulse-height information but not rate information are flagged and not used in any later calculations. Finally data gaps are replaced with null readings. The output of this step is a time ordered and continuous data set which contains only good rate readings and good PHA events, with their previously calculated charges and masses. It is this data set which is considered in all flux calculations.

The program FLUXGEN calculates absolute fluxes from the above generated data set. FLUXGEN allows considerable flexibility in the absolute flux calculation. Elemental fluxes, galactic isotopic fluxes, and solar isotopic fluxes are incorporated in the range of possibilities of the program. It is also possible to select multiple time periods, multiple energy ranges and/or multiple geomagnetic positions of the spacecraft. Once the type of flux calculation is chosen it is also possible to specify more stringent restrictions on a PHA event when considering whether to count the event in the flux calculation. Two extra tests are used in the CHIME validation presented here:

a) the ratio of the energy losses in adjacent PSDs must be consistent with an absence of nuclear interactions in the telescope, and;

b) the PHA event must stop far enough from the edge of the detector so that there is little possibility of energy loss into the non-responsive detector mountings (edge effect).
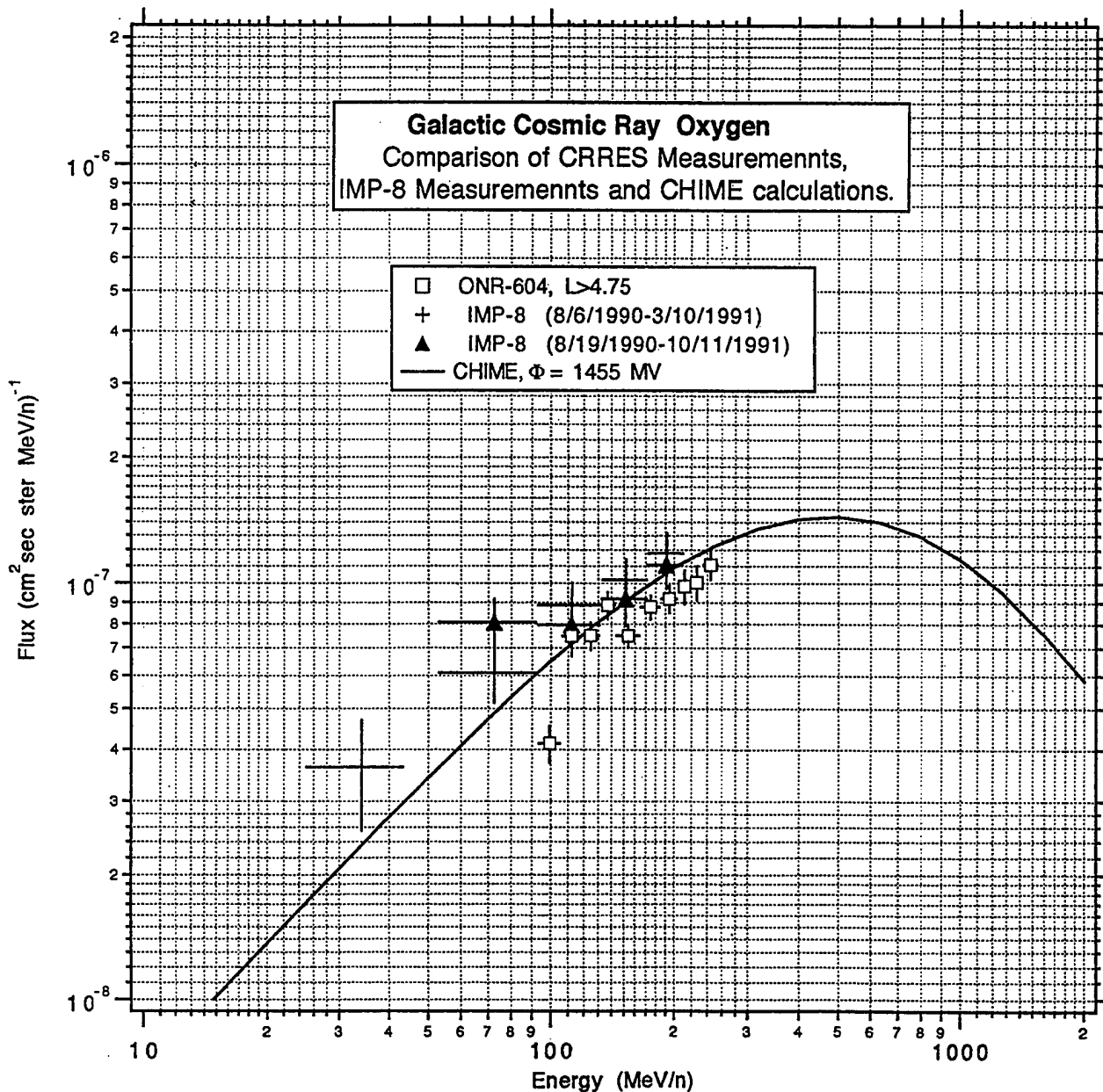
The program FLUXGEN first totals the number of PHA events of requested element (Z) which stop in each of the eight Kevexes. These totals are normalized to the geometrical factor corresponding to the particular detector in which the PHA events stopped. The geometrical factors for each of the detectors in the Chicago telescope were determined with a Monte-Carlo calculation. The totals are further normalized by the appropriate rates (P1 rate, P2 rate or P3 rate) as previously calculated in RATEFIX. Lastly the totals are normalized by the collection time and differential energy range requested. These values are used in the calculation of the absolute differential energy fluxes for each of the elements H through Ni.

The outputs of the FLUXGEN program were checked by an analytic method calculating fluxes using dE/dx vs. E matrix displays.

Because during the time of the CRRES mission the solar modulation level had strong variations, the ONR-604 quiet time data has been divided in 3 periods, characterized by the values of the modulation parameter $\Phi = 1351$ (low modulation), $\Phi = 1432$ (intermediate modulation), and $\Phi = 1589$ (high modulation). The average modulation for the total CRRES period is $\Phi = 1455$.
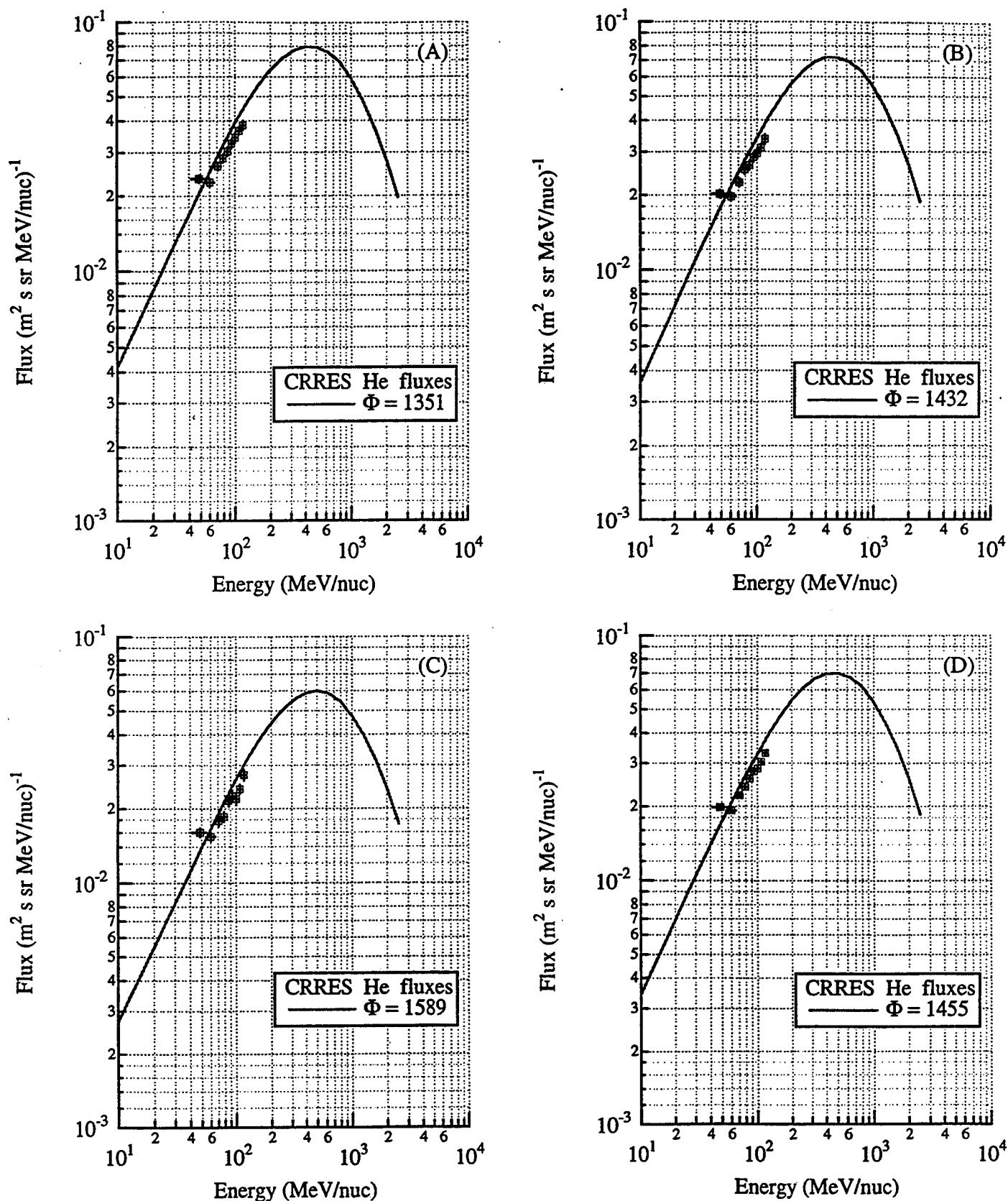
The oxygen fluxes calculated with ONR-604 data for the total CRRES mission are compared in FIGURE 4 to fluxes calculated with IMP-8 satellite data for both an identical time period an another overlapping period. As can be seen the agreement between the two instruments is within the error limits. The figure also shows the good agreement of the CHIME model prediction (solid curve) with the experimental results.

FIGURES 5, 6 and 7 show the comparisons of the experimental ONR-604 fluxes with the CHIME predictions for the 4 modulation levels, for quiet time galactic cosmic ray helium, oxygen and iron. The close agreement shows the accuracy of the CHIME model and its good sensitivity to variations of the modulation level.
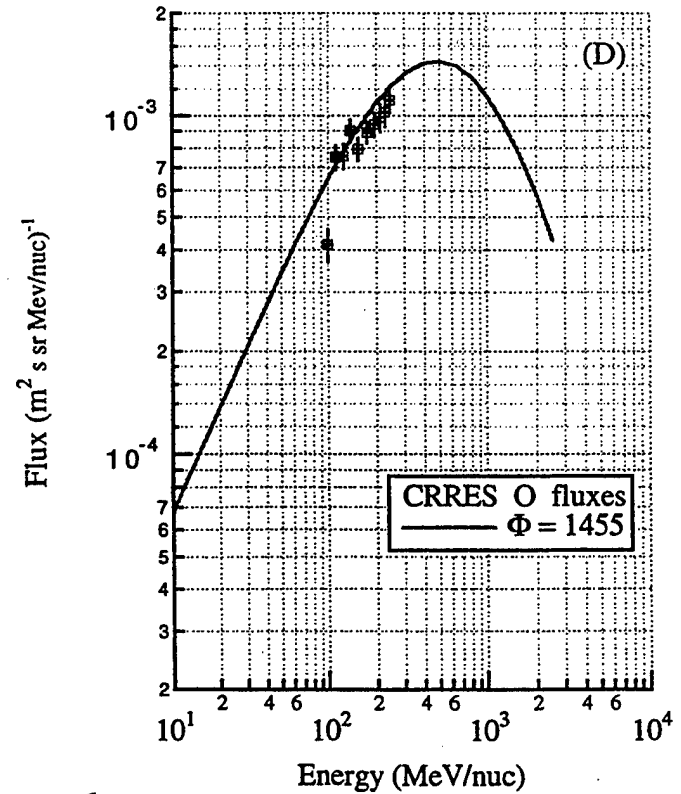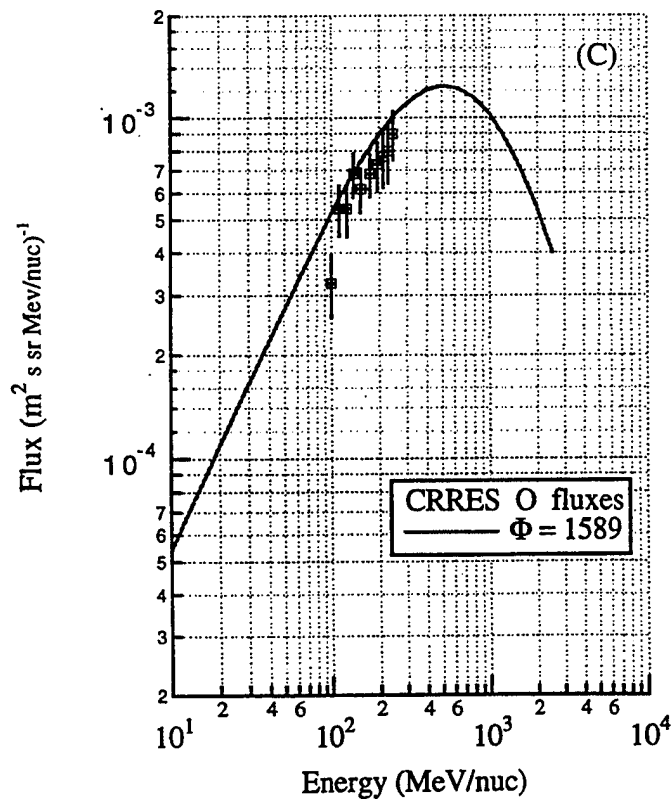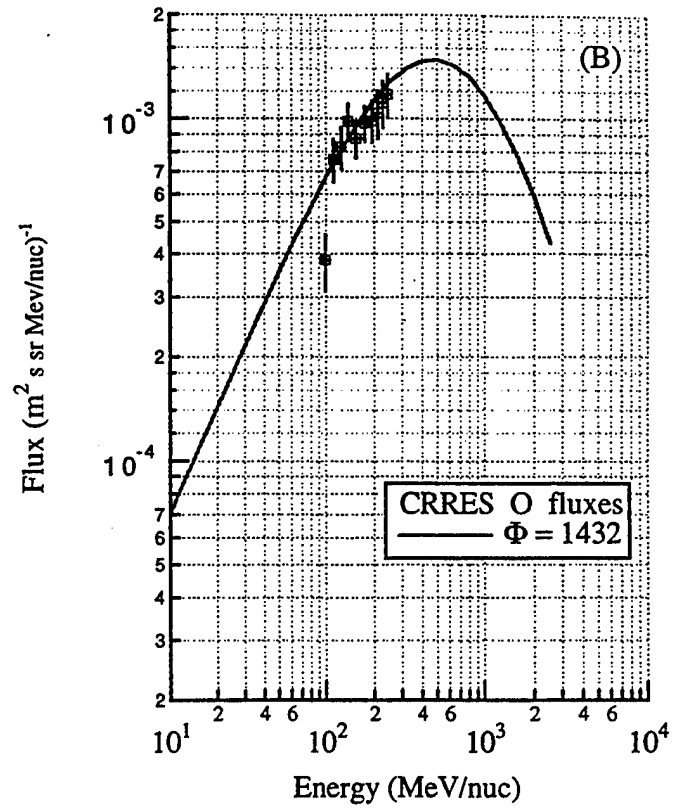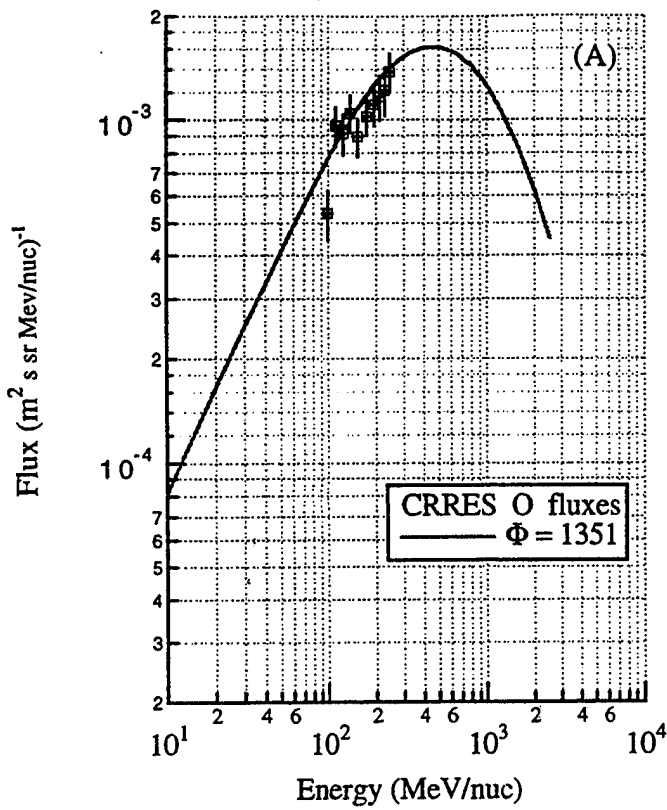

Galactic Cosmic Ray Oxygen
Comparison of CRRES Measuremennts,
IMP-8 Measuremennts and CHIME calculations.

□ ONR-604, L>4.75
+ IMP-8 (8/6/1990-3/10/1991)
▲ IMP-8 (8/19/1990-10/11/1991)
—— CHIME, Φ = 1455 MV

Figure 4

CRRES Helium Fluxes and
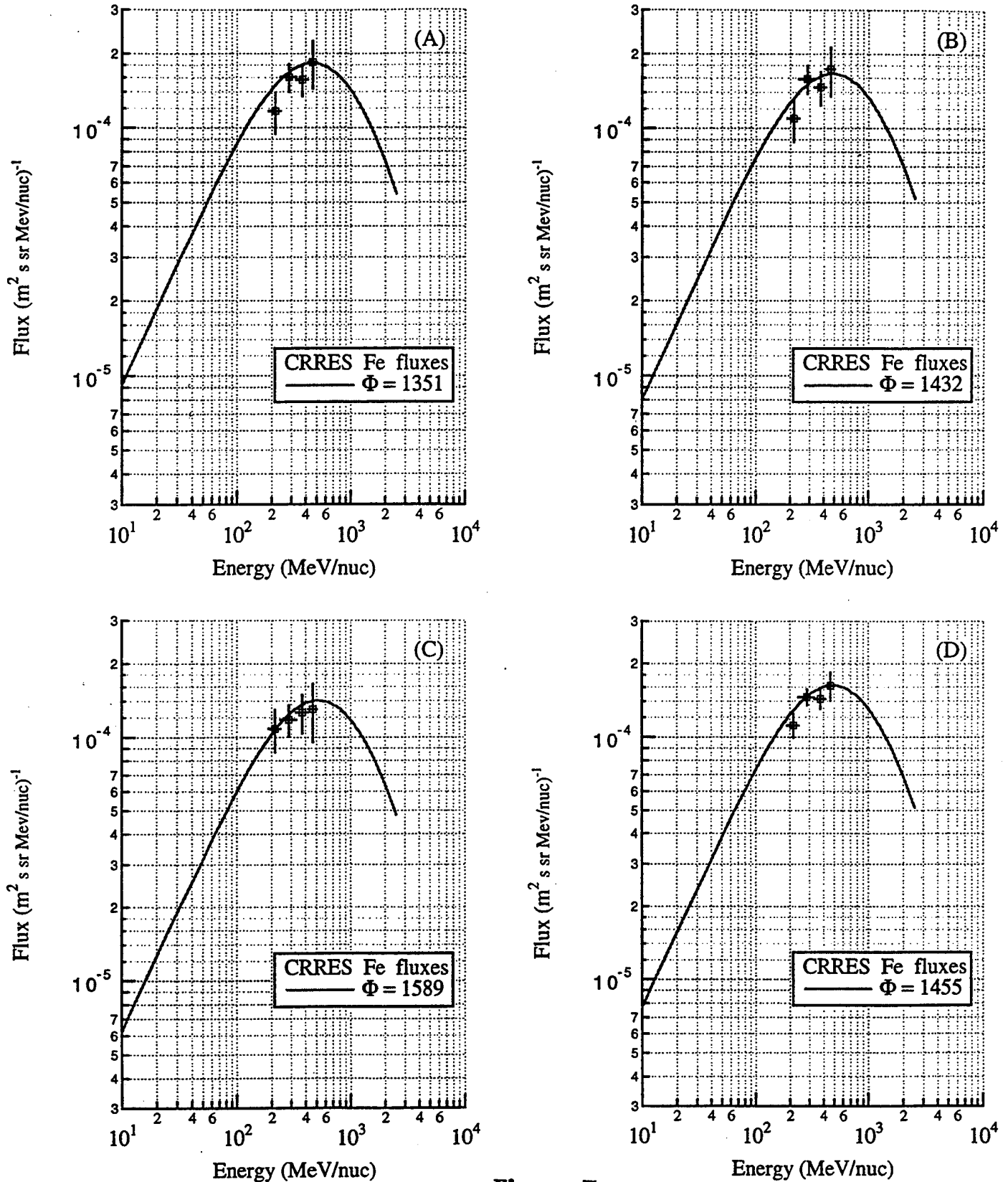# CHIME Theoretical Model

Figure 5

CRRES Oxygen Fluxes and
CHIME Theoretical Model

Figure 6

CRRES Iron Fluxes and
CHIME Theoretical Model

Figure 7

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4. SCIENTIFIC INVESTIGATIONS

The scientific investigations using ONR-604 data have been conducted mainly in two areas: a) Access of heavy ions into the Earth's magnetosphere and b) Isotopic composition of galactic cosmic rays.

1. Access of Heavy Ions into the Earth's Magnetosphere (*Papers 1, 9 in the Appendix*)

In order to study the access of heavy energetic particles into the Earth's magnetosphere quiet time events measured by ONR-604 were traced through a Tysganenko geomagnetic field model to determine the cutoff rigidities. The effective charge for each event was determined by comparison with the measured energy. Finally the distribution of L values was plotted as a function of the effective charge. It was found that there is not strong evidence (at the 1-2% level) that during quiet times and in the energy range of the particles measured by ONR-604, partially ionized heavy nuclei have magnetospheric access below cutoff rigidity.

Looking at the case of flare particles it was found that during a flare period the distribution of L values as a function of particle energy is practically uniform indicating that the particle events have a purely interplanetary origin.

2. Isotopic Composition of Galactic Cosmic Rays (*Papers 2, 3, 4, 10 in the Appendix*)

The University of Chicago ONR-604 experiment has the highest mass resolving power currently reported among the space cosmic ray telescopes This high mass resolution has been applied, using ONR-604 data, to the study of the isotopic abundances of the space heavy energetic particles. Unfortunately the unexpected cessation of the CRRES mission on October 1991 limited the amount of data available for studies of problems like the isotopic composition of rare cosmic ray and low abundance elements in solar events.

For many years measurements have been made to determine the isotopic ratios of the "medium-weight" elements, e.g. C through Si, and to calculate a corresponding source abundance of these ratios. Knowledge of these source abundances can, for example, allow to place constraints on particular stellar models of cosmic-ray production (e.g., the Wolf-Rayet model or the "supermetallicity" model), or they could be compared with the solar system abundances to acquire information about the chemical evolution of the Galaxy.

Before 1992, reported measurements gave a picture for these medium-weight cosmic-ray isotopes that seemed more or less clear as to their isotopic source abundances. Most of the measurements were consistent with either solar system abundances at the source, or with a suppression at the source (in the case of nitrogen). However some of the isotopes were reported overabundant at the source relative to the solar system abundances.

During the period covered by this report the isotopic composition of the cosmic ray elements C, N, O, Ne, Mg, and Si were measured over the energy interval 98-364 MeV/n using data returned by the University of Chicago ONR-604 experiment on board the CRRES satellite. The experimental mass resolution for these isotopes was $\sigma = 0.14$ to 0.19 amu. FIGURES 8 and 9 illustrate the complete isotope separation reached in these analysis.
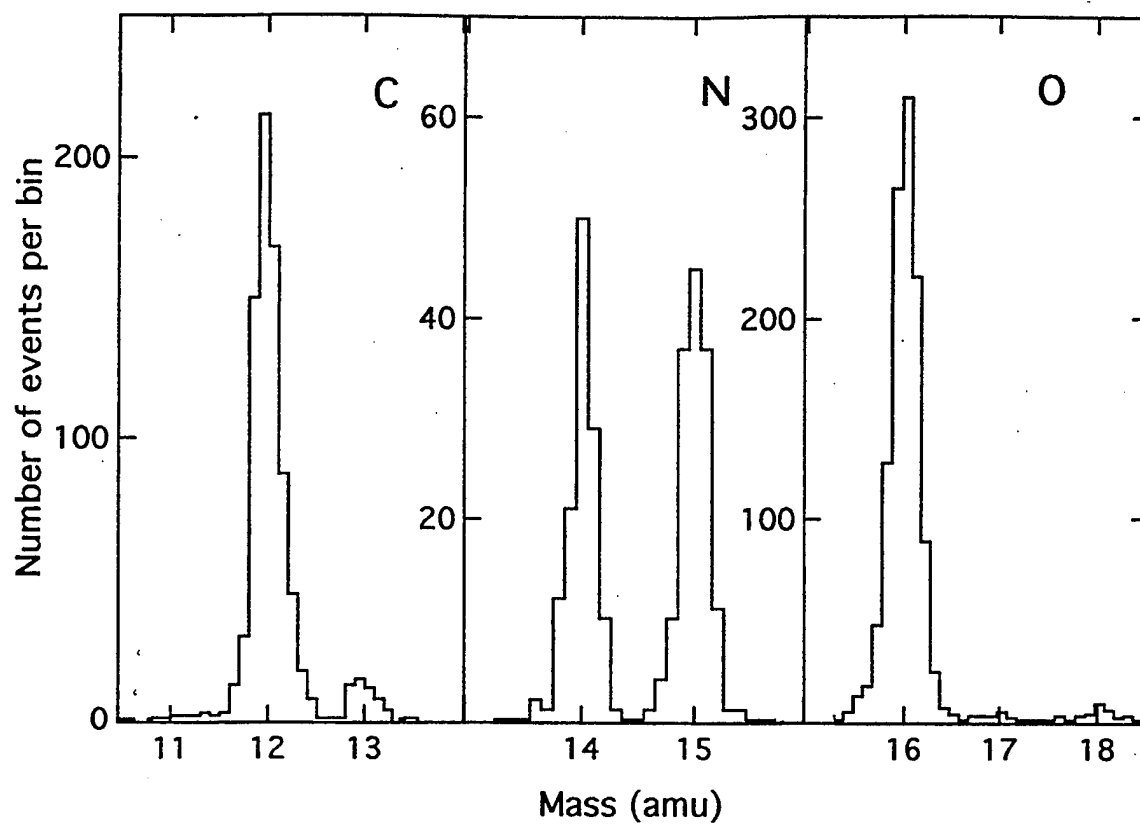
Figure 8
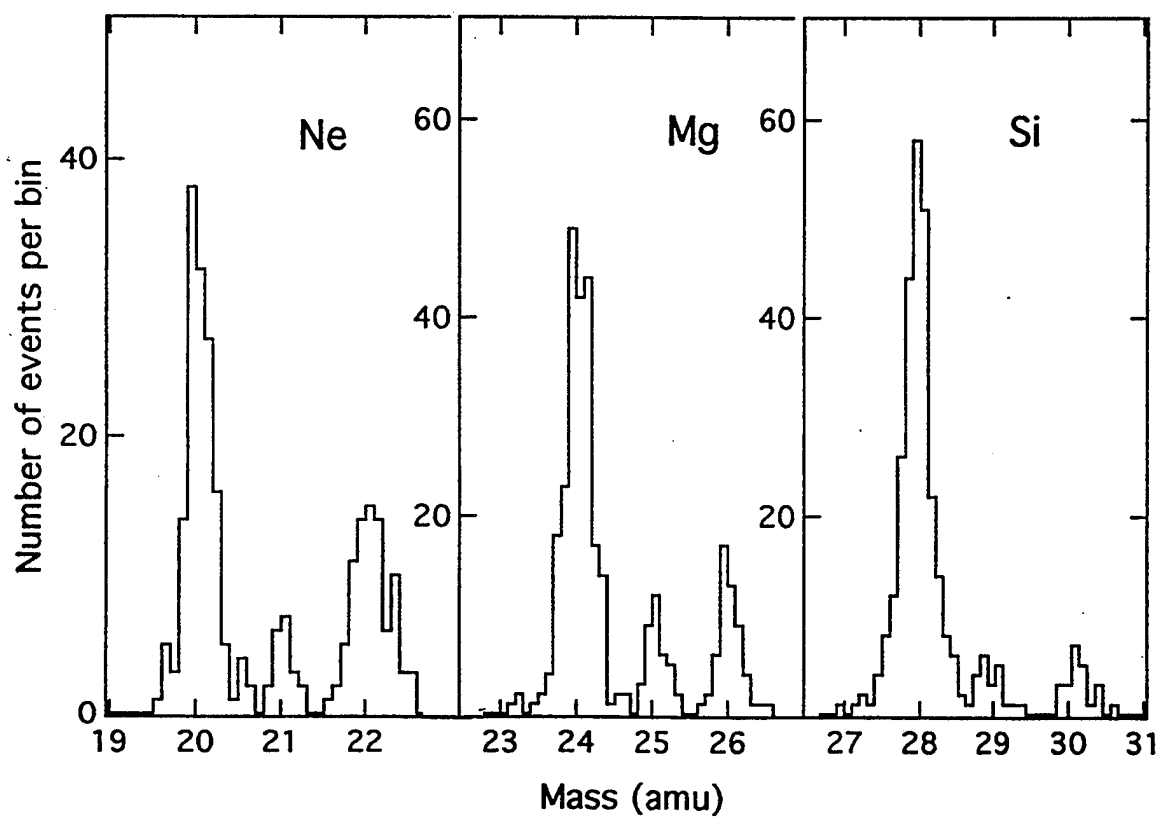
Figure 9

Using a propagation model described developed by our group (Garcia-Munoz *et al.* Ap. J. Suppl., 64, 269, 1987), we calculated source abundances for these isotopes and found the secondary isotopes ^{13}C, ^{15}N, ^{17}O, ^{18}O, ^{21}Ne, ^{25}Mg, ^{26}Mg, ^{29}Si, and ^{30}Si to be either consistent with solar system abundances or absent from the source. The source ratio $^{22}Ne/^{20}Ne$ was found to be a factor 3.0 larger than in the solar system.

These results have led to a revision of some nucleosynthesis theories which had previously been widely accepted as origin of the above isotopes.

APPENDIX

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2. M. A. DuVernois, M. Garcia-Munoz, K. R. Pyle, and J. A. Simpson. "The Isotopic Composition of Ne, Mg, and Si Cosmic Rays from the ONR-604 Experiment on the CRRES Mission", *Proc. XXIII Int'l Cosmic Ray Conf., (Calgary)*, 1., 563, 1993.

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4. M. Garcia-Munoz, K. R. Pyle, J. A. Simpson, and M. Thayer, "The Isotopic Composition of Cosmic Ray C, N, O: Source Abundances Derived from the ONR-604 Experiment on the CRRES Mission", *Proc. XXIII Int'l Cosmic Ray Conf., (Calgary)*, 1., 543, 1993.

Papers submitted for publication :

5. J. Chen, D. Chenette, T. G. Guzik, M. Garcia-Munoz, K. Pyle, Y. Sang and J. Wefel. "A Model of Solar Energetic Particles for Use in Calculating LET Spectra Developed from ONR-604 Data" submitted for publication in Adv. Space Res.

6. J. Chen, D. Chenette, T. G. Guzik, M. Garcia-Munoz, K. Pyle, Y. Sang and J. Wefel. "A Model of Galactic Cosmic Rays for Use in Calculating LET Spectra", submitted for publication in *Adv. Space Res.*

Papers in preparation :

7. D. Chenette, J. Chen, E. Clayton, T.G. Guzik, J.P. Wefel, M. Garcia-Munoz, C. Lopate, K.R. Pyle, K.P. Ray, E.G. Mullen, and D.A. Hardy, "The CRRES/SPACERAD Heavy Ion Model of the Environment (CHIME) for Cosmic Ray and Solar Particle Effects on Electronic and Biological Systems", paper G-1 at the *"31st Annual International Nuclear and Space Radiation Effects Conference"*, Tucson, Arizona, July 18-22, 1994.

8. D. Chenette, M. Garcia-Munoz, T.G. Guzik, C. Lopate, K.R. Pyle, J.A. Simpson, and J.P. Wefel, "The Heavy Ion Model of the Environment (CHIME) for Cosmic Ray and Solar Particles", to be submitted to the *Astrophys. Journal Suppl.*

9. J. Chen, T.G. Guzik, J.P. Wefel, K.R. Pyle, M. Garcia-Munoz, J.A. Simpson, and J.F. Cooper, "Energetic ^{3}He Radiation Belt at L = 1.1 - 2.3" , in preparation.

10. M.A. DuVernois, M. Garcia-Munoz, K.R. Pyle, M. Thayer, and J.A. Simpson,"The Isotopic Composition of Galactic Cosmic Rays from the ONR-604 Experiment on the CRRES Mission", to be submitted to the *Astrophys. Journal.*