NSR 21-002-224

IONIZATION STATES OF HEAVY ELEMENTS OBSERVED IN THE 1974 May 14-15 ANOMALOUS SOLAR PARTICLE EVENT

L.S. Ma Sung[1], G. Gloeckler[1], C.Y. Fan[2], and D. Hovestadt[3]

[1]Department of Physics and Astronomy
University of Maryland, College Park, MD 20742 USA

[2]Department of Physics, University of Arizona, Tucson, AZ 85721 USA

[3]Max-Planck-Institut fur Physik und Astrophysik
8046 Garching b. Munchen, West Germany

(NASA-CR-163932) IONIZATION STATES OF HEAVY ELEMENTS OBSERVED IN THE 1974 MAY 14-15 ANOMALOUS SOLAR PARTICLE EVENT (Maryland Univ.) 15 p HC A02/MF A01 CSCL 03B

N81-17973

Unclas
G3/92 43967

UNIVERSITY OF MARYLAND
DEPARTMENT OF PHYSICS AND ASTRONOMY
COLLEGE PARK, MARYLAND

IONIZATION STATES OF HEAVY ELEMENTS OBSERVED IN THE 1974 May 14-15 ANOMALOUS SOLAR PARTICLE EVENT

L.S. Ma Sung[1], G. Gloeckler[1], C.Y. Fan[2], and D. Hovestadt[3]

[1]Department of Physics and Astronomy
University of Maryland, College Park, MD 20742 USA

[2]Department of Physics, University of Arizona, Tucson, AZ 85721 USA

[3]Max-Planck-Institut fur Physik und Astrophysik
8046 Garching b. Munchen, West Germany

Received __________

ABSTRACT

We have determined the charge states of heavy ions accelerated in the ^{3}He-Fe rich solar particle event of 1974 May 14-15 using data from the University of Maryland/Max-Planck-Institut experiment on IMP-8. In addition to $Fe^{+11,12}$ we find that both O^{+5} and $Fe^{+16,17,18}$ are also present suggesting variations in coronal temperatures over a range from $\sim 4 \times 10^5$ to 5×10^6 °K. The presence of O^{+5} and Fe^{+16-18} may be explained by a resonant plasma heating mechanism proposed by Fisk (1978) to account for the enhancements of ^{3}He and Fe.

I. INTRODUCTION

The discovery of dramatic departures of the composition in ^{3}He- and Fe-rich solar particle events (Hovestadt et al. 1975; Hurford et al. 1975; Serlemitsos and Balasubrahmanyan 1975; Gloeckler 1979) from solar abundances has provided new insight into conditions and preacceleration processes at the flare site. In order to explain the enormous enrichment of ^{3}He in these anomalous events, it has been proposed (Fisk 1978; Ibragimov, Kocharov and Kocharov 1978) that plasma processes selectively heat certain ion species which then are accelerated to the observed energies of up to several MeV/nucleon. Because these preferential heating models make predictions on the charge states of the overabundant ions, it is especially important to measure the ionization states of the energetic particles in these anomalous events.

In this paper we report our analysis of the charge states of low energy (76-1000 keV/charge) heavy ions in the 1974 May 14-15 solar particle event. This event has been selected not only because the $\lesssim$1 MeV/nucleon intensity of heavy ions was sufficiently large ($\sim$50/cm^2-sec-sr-MeV/nuc at 50 keV/nuc) to permit charge-state analysis but also because detailed information is available on the elemental and isotopic composition for this event. We find that in addition to Fe^{+11} and Fe^{+12}, reported in our previous publication (Gloeckler et al. 1976), significant amounts of Fe^{+16} to Fe^{+18} are also present, especially above $\sim$600 keV/charge. We explain these results on the basis of the resonant heating mechanism by ion cyclotron waves proposed by Fisk (1978). Furthermore, we infer from the observed charge states that coronal temperatures extended over a broad range (4×10^5 to 5×10^6 ^{o}K) at the time of this flare.

II. INSTRUMENTATION

Our measurements were carried out using the Electrostatic Energy-versus-Charge Analyzer (EECA) of the University of Maryland/Max-Planck-Institut experiment on IMP-8. The EECA sensor consists of an electrostatic deflection system and eight rectangular solid state detectors (Tums et al. 1974). Ions in the range 44-1220 keV/charge are analyzed in seven discrete energy-per-charge intervals fixed by the locations and widths of the solid-state detectors. Pulse-height analysis of the total kinetic energy in each of the solid state detectors makes it possible to determine the ionization (or charge) state of the incoming ions. We note however that the EECA cannot determine the atomic number of the particle. This information is provided by the dE/dx vs E ULET sensor (Hovestadt and Volmer 1971) which is also part of the University of Maryland/Max-Planck-Institut experiment on IMP-8.

III. CHARGE STATES OF HEAVY IONS IN THE ^{3}He-Fe-RICH EVENT

Fig. 1(a) shows the energy histogram derived from pulse-height data over a 22-hour time period during the 1974 May 14-15 ^{3}He-Fe-rich solar particle event. Because the ionization states are roughly proportional to the measured energy in a given detector (Sciambi 1975; Ma Sung et al. 1980) the energy histogram may be used to deduce the ionization states of incoming particles. Thus, the histogram of Fig. 1(a) shows 3 distinct charge peaks corresponding to protons (charge Q=1), alpha particles (Q=2) and heavy ions (Q≥4). Because of insufficient charge resolution, heavy ions of various charge states overlap to form a single peak. Nevertheless, it is possible to determine the charge distribution by synthesizing a pulse-height profile using the instrument response for an energetic ion population of a given elemental composition, a charge-state distribution and a spectral shape (Sciambi 1975; Ma Sung et al. 1980), and comparing this with the measured histogram. In Figure 1(a), the dotted, dashed and dashed-dotted curves are the calculated pulse-height distributions for an ion population with elemental abundances given by the ULET sensor at ∿1 MeV/nuc (columns 5 and 6 of Table 1) and a charge-state distribution assuming ions in equilibrium (Jordan 1969) with a coronal plasma of 1.0, 1.6 and 2.0 x 10^{6} °K degrees respectively. Given the equilibrium temperature and the elemental abundances of the ions, the shape and the position of the ion distribution is fixed. The amplitude of each of the calculated distributions is obtained by a χ-square fit to the data. We find that the observed distribution cannot be adequately accounted for by any of the fits. This is contrary to the case for "normal composition" flare particle events. Thus for the event on 1973 November 4-5 shown in Fig. 1(b), the charge states are consistent with an equilibrium charge distribution at ∿1.6 x 10^{6} °K (Sciambi et al. 1977; Ma Sung et al. 1979) and with the absence of either low ($Q<5$) or high ($Q\gtrsim15$) ionization states. The anomalous event (Figure 1(a)), on the other hand, appears to be rich in both the low (Q=5-7) and the high (Q=16-18) charge states, as can be seen by comparing the pulse-height histogram with calculated profiles. The unusually high abundance of iron in this event (see Table 1) makes it easy to identify the charge 16-18 particles as iron. The large excess of charge 5 particles could be either carbon or oxygen. Since this event is known to be depleted in carbon (Mason, Gloeckler and Hovestadt 1979), we conclude that these $Q = 5$ ions are O^{+5}. The presence of O^{+5} suggests ions are accelerated from an ambient plasma of low temperature, i.e. of $\sim4 \times 10^5$ °K (Jordan 1969). The presence of Fe^{+17} indicates a temperature in excess of 5×10^6 °K (Jordan 1970). Therefore, we conclude that the observed ions probably originated in regions where the coronal temperature varied over this range.

The presence of O^{+5} and Fe^{+17} in this event appears to be consistent with the plasma heating mechanisms suggested by Fisk (1978). According to this model, ^3He is preferentially heated by electrostatic ion cyclotron waves whose frequency ω is in resonance with the first harmonic of the ^3He gyrofrequency. In addition to ^3He, partially stripped ions with the second harmonic of their gyrofrequency near ω would also be selectively heated. These ions would have charge-to-mass ratios $Q/A \sim 1/3$ and would include O^{+5} and Fe^{+17}.

To examine our observations in terms of Fisk's plasma heating model, we compre the histograms in detectors P3 and P7 with calculated distributions based on the ionization states prescribed by Fisk's model. For the more abundant elements (see Table 1, column 6), this leads to O^{+5}, Ne^{+6}, Mg^{+7}, Si^{+8}, Si^{+9}, S^{+9}, S^{+10} and $Fe^{+16,17,18}$, with charge-to-mass ratios in the range of 0.28 to 0.32, i.e., in the neighborhood of 1/3 as required. A χ-square fit to the data using these charge states and abundances measured by the ULET sensor leads to a calculated distribution which is somewhat deficient in elements with charge states 11-12.

Since this event is highly overabundant in iron, it is concluded that the missing ions are likely to be $Fe^{+11,+12}$. For convenience of fitting, only Fe^{+12} and Fe^{+17} are arbitrarily chosen, although the instrument resolution is not sufficient to separate Fe^{+11} from Fe^{+12} or Fe^{+17} from Fe^{+16} and Fe^{+18}.

We can estimate the fluxes of Ne-S, O^{+5}, Fe^{+12} and Fe^{+17} by performing a χ-square analysis for the heavy ion pulse-height data in each detector. The following approach is used in this analysis.

1) Initially, the energy-per-nucleon spectra of all ions are assumed to be identical. The common spectrum is determined by summing up all pulse-height counts in the heavy ion peak in each detector and plotting the resulting flux versus energy per nucleon (Ma Sung _et al_. 1980).

2) For simplicity, and because of the limited charge resolution, we assume the abundances of neon to sulfur relative to silicon to be given by the ULET measurements (Table 1, column 6). Nitrogen and carbon have been neglected since their abundances are low compared to oxygen.

3) The abundances of Si^{+8} and Si^{+9} are assumed to be equal, as are those of S^{+9} and S^{+10}.

4) The absolute abundances of Ne-S, O^{+5}, Fe^{+12} and Fe^{+17} are left as free parameters to be determined by the χ-square fit.

5) The best estimates of the differential fluxes of Ne-S, O^{+5}, Fe^{+12} and Fe^{+17} are obtained respectively in each of the energy/charge intervals (i.e. P2, P3 and P7) by minimizing the χ-square. The spectra so obtained are used as the next generation input parameters, and the whole process is repeated. We terminate the iteration when the spectra generated are equal to the input spectra. This process allows an internally consistent determination of the fluxes and spectra for each of the ion species within each energy window.

Figure (2) shows the observed pulse-height histogram for heavy ions in P7 (692-1000 keV/charge). The dashed curve is the calculated pulse-height distribution using the approach specified above. The arrows in the figure indicate the energies at which each species peaks in its contribution. The reduced χ-square for 4 degrees of freedom is 1.1 for the fit, which gives an integral probability of 0.45 for having a χ-square larger than 1.1. For P3 (163-238 keV/charge), a similar fit shows a reduced χ-square of 1.5 for 5 degrees of freedom, corresponding to an integral probability of 0.2. These χ-square values indicate that the fits are reasonable.

It should be pointed out that while only Fe^{+12} and Fe^{+17} have been included in our fitting procedure, other possibilities have also been examined. For example, we found that the observed pulse-height distribution cannot be reproduced by assuming for iron either (a) only charge states 10 to 12, as in the case for normal flare events, or (b) a distribution of charge states from 11 to 18 peaking around 15, or (c) only charge states 16 to 18, as required by Fisk's model. Instead two charge-state groups for iron are required. One in the range of 11 to 12, the other from 16 to 18, centered at $\sim$17. The relative amount of iron in these two charge-state groups are $Fe^{+12}/Fe^{+17} = 0.65 \pm 0.34$ at $\sim$0.15-0.30 MeV/nuc.

While the abundances of Fe^{+12} and Fe^{+17} in detectors P3 and P7 are determined assuming that the composition of neon to sulfur stays relatively constant with energy, our results will not change significantly if the neon to sulfur relative abundances vary with the energy. This is because no other elements have charge states close to Fe^{+17}, and the only other ions whose charge states lie close to those of Fe^{+12} are S^{+10}, whose abundances at equal energy per charge are lower than those of iron.

IV. SUMMARY AND CONCLUSIONS

The charge-state analysis of heavy ions in the ^{3}He-Fe-rich solar particle event of 1974 May 14-15 allows us to state the following results:

1. The large abundances of charge state 5 ions and the extremely low abundance of carbon compared to oxygen (Mason, Gloeckler and Hovestadt 1979) argues strongly that O^{+5} is among the most abundant heavy ions accelerated in this flare.

2. The presence of significant amounts of ions with charge states above 15 leads us to conclude that iron with high ionization states ($Fe^{+16,17,18}$) is also accelerated.

3. The observation of ionization states 11 to 12 combined with the measured S/Fe ratio of 0.4 at 1.0-4.6 MeV/nuc (see Table 1) implies that lower charge states of iron ($Fe^{+11,+12}$) co-exist with the higher charge states in about equal proportions.

We believe our results have far reaching implications for determining conditions in the flare regions where these ions are accelerated. First, the co-existence of both low (O^{+5}) and high (Fe^{+17}) charge states suggests that in this anomalous flare, ions were probably accelerated from an ambient plasma whose temperatures ranged from $\sim 4 \times 10^5$ to 5×10^6 °K. This is in contrast to the case for normal flares where a single coronal temperature (typically $1\text{-}2 \times 10^6$ °K) can account for the charge-state observations (Sciambi et al. 1977). Second, our charge-state measurement may be explained in terms of the resonant heating mechanism proposed by Fisk (1978) for the ^{3}He and the heavy ion rich events. In Fisk's model, heavy ions which have charge-to-mass ratios $Q/A \sim 1/3$ are preferentially heated by electrostatic ion cyclotron waves. On the other hand, the heating mechanisms of Ibragimov, Kocharov and Kocharov (1978) requires lower ionization states of iron than those we observe. Third, our observations of $Fe^{+11,12}$ suggest that for iron resonance heating by the waves whose frequency lies near the third harmonic of the ion gyrofrequency may also be important. The required charge-to-mass ratio to fulfill this condition would be $Q/A \sim 0.22$, which corresponds to Fe^{+12}. Finally, just as elemental abundances and charge-state measurements in flare particle events have been essential for a better understanding of the preacceleration process, the energy dependence of the composition will be crucial for delineating the flare acceleration mechanisms. This question will be addressed to in greater detail in our future work.

ACKNOWLEDGEMENTS

We are grateful to the many individuals at the University of Maryland and the Max-Planck-Institut who have contributed to the successful operation of the IMP-8 instrument over the years. G. M. Mason is acknowledged for his valuable comments on particle composition. Ms. Mary Lou Snidow is gratefully appreciated for her careful preparation of the manuscript. This work was supported in part by the National Aeronautics and Space Administration under contract NAS5-11063 and grant NGR 21-002-224 and by the German government.

REFERENCES

Fisk, L.A., 1978, Ap.J., 224, 1048.

Gloeckler, G., 1979, Rev. Geophys. Space Phys., 17, 569.

Gloeckler, G., Sciambi, R.K., Fan, C.Y., and Hovestadt, D., 1976, Ap.J. (Letters), 209, L93.

Hovestadt, D., Klecker, B., Vollmer, O., Gloeckler, G., and Fan, C. Y., 1975, 14th Internat. Cosmic Ray Conf. (Munich: Max Planck Institut fur extraterrestrische physik), 5, 1613.

Hovestadt, D. and Vollmer, O., 1971, 12th ICRC at Hobart, 4, 1608.

Hurford, G.J., Mewaldt, R.A., Stone, E.C. and Vogt, R.E., 1975, Ap.J. (Letters), 201, L95.

Ibragimov, J.A., Kocharov, G.E., and Kocharov, L.G., 1978, Academia Nauk USSR, A.F. Joffe Phys. Techn. Inst., Nr. 588.

Jordan, C. 1969, Mon. Not. R. Astr. Soc., 142, 501.

________. 1970, Mon. Not. R. Astr. Soc., 148, 17.

Ma Sung, L. S., Gloeckler, G., Fan, C. Y. and Hovestadt, D., 1979, 16th Internat. Cosmic Ray Conf. (Kyoto: Science Council of Japan and Physical Society of Japan), 12, 271.

Ma Sung, L. S., Gloeckler, G., Fan, C. Y., and Hovestadt, D., 1980, accepted for publication in J. Geophys. Res.

Mason, G.M., Gloeckler, G., and Hovestadt, D., 1979, Ap.J. (Letters), 231, L87.

Mobius, E., Hovestadt, D., Klecker, B., and Gloeckler, G., 1980, accepted by Ap.J.

Sciambi, R.K., 1975, Ph.D. Thesis, University of Maryland.

Sciambi, R.K., Gloeckler, G., Fan, C.Y., and Hovestadt, D., 1977, Ap.J., 214, 316.

Serlemitsos, A.T., and Balasubrahmanyan, V.K., 1975, Ap.J., 198, 195.

Tums, E., Gloeckler, G., Fan, C.Y., Cain, J., and Sciambi, R.K., 1974, IEEE Trans. Nucl. Sci., NS-21, No. 1, 210.

Table 1

Abundance Ratios in a ^{3}He- and Fe-Rich Event and a Normal Solar Particle Event

	^{3}He-Iron-Rich Event 1974 May 14-15 Energy range (MeV/nucleon)					Normal Flare Event 1973 November 4-5
Element Ratio	0.03-0.06[a]	0.2-0.3[a]	0.44-1.1[b]	0.6-1.6[c,d]	1.0-4.6[d]	1.0-4.6[d]
$^{1}H/^{4}He$			33±3	25±3		
$^{3}He/^{4}He$			0.56±0.08	0.29±0.08		
C/O				$0.01^{+0.07}_{-0.01}$		0.67±0.19
N/O				0.12±0.10		
Ne/O					0.35±0.15	0.04±0.04
Mg/O					0.40±0.17	0.13±0.08
Si/O					0.30±0.14	0.13±0.08
S/O					0.45±0.18	0.08±0.06
$Fe^{+11,12}/O$	0.13±0.14	0.8±0.6				
Fe^{16-18}/O	0.16±0.09	1.2±0.8		2.58±0.57	1.10±0.34	0.04±0.04
Fe/He	0.01±0.005	0.05±0.01		0.06±0.01	0.06±0.01	

(a) This work, EECA data
(b) Mobius *et al.*, 1980
(c) Mason *et al.*, 1979
(d) This work, ULET data

FIGURE CAPTIONS

Figure 1 Pulse-height distributions of protons, alpha particles and heavier ($Z>2$) ions in detector P3. (a): Distributions for the anomalous flare event on 1974 May 14-15. (b): Distributions for a "normal composition" flare event on 1973 November 4-5. The dashed curves are calculated by folding the instrument response for a given ion species whose input energy-per-nucleon spectrum (shown in the figure) is determined by summing up pulse-height counts in each charge peak and for each detector. For heavy ions, the elemental abundances (given in Table 1 columns 6 and 7 for the two events respectively) and a change-state distribution for the ions are also necessary as input parameters. The dotted, dashed, and dashed-dotted curves superposed on the heavy ion peaks are calculated curves assuming ions in charge equilibrium (Jordan 1969) at a coronal temperature of 1.0, 1.6 and 2.0 x 10^6 ^{o}K respectively. Note that while the assumption of 1-2 x 10^6 ^{o}K coronal temperatures describes the ionization states of heavy ions adequately for a normal flare event, it fails to do so for the anomalous flare event.

Figure 2 Pulse-height histogram of heavier ($Z>2$) ions in detector P7 for the anomalous flare event on 1974 May 14-15. The dashed curve shows the χ-square fit for a calculated distribution assuming that relative abundances of Ne to S relative to Si are given by ULET abundances, and that ionization states are specified by Fisk's (1978) plasma heating model. The positions where the contribution of each ion species peaks are indicated by the arrows.

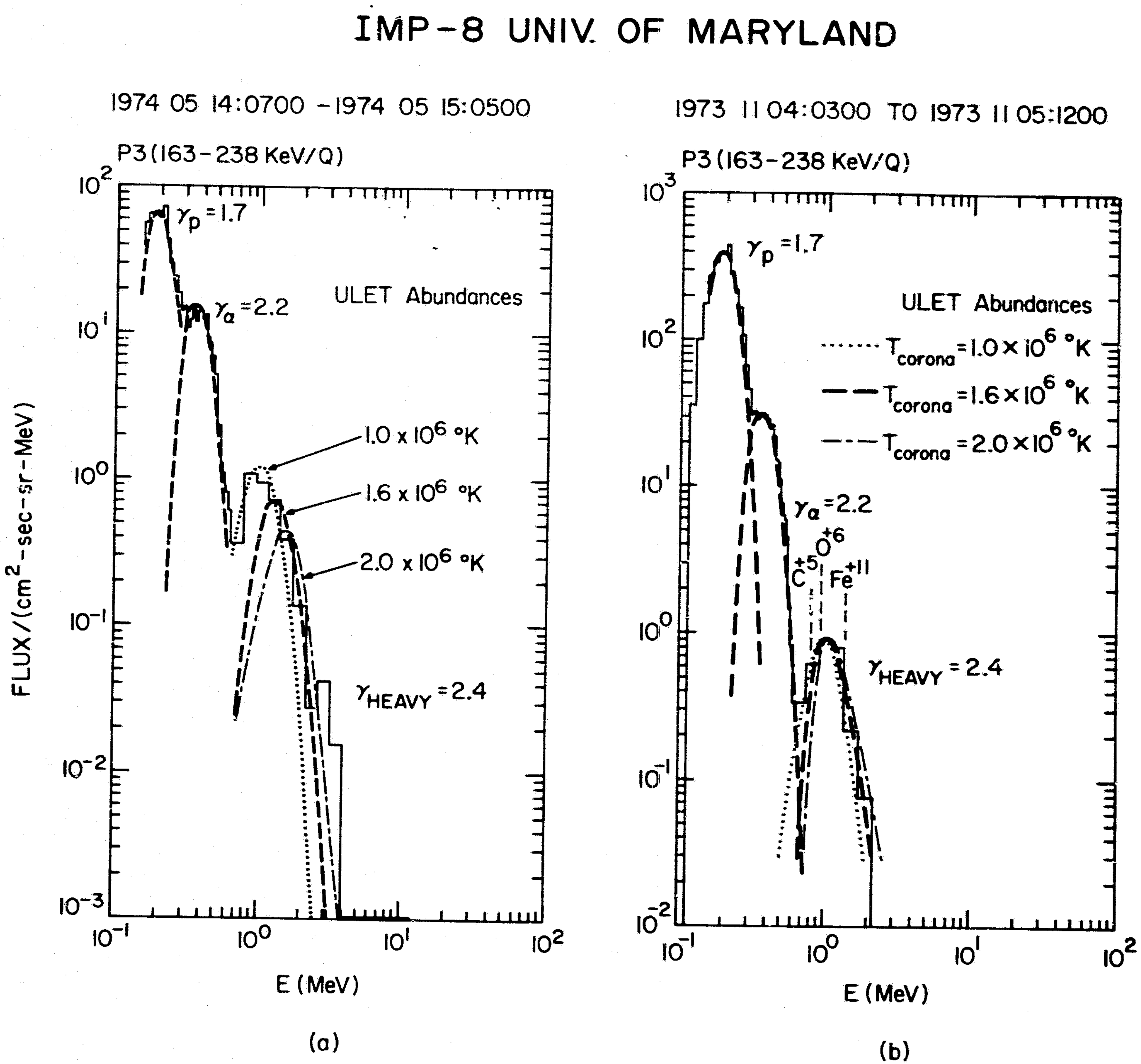
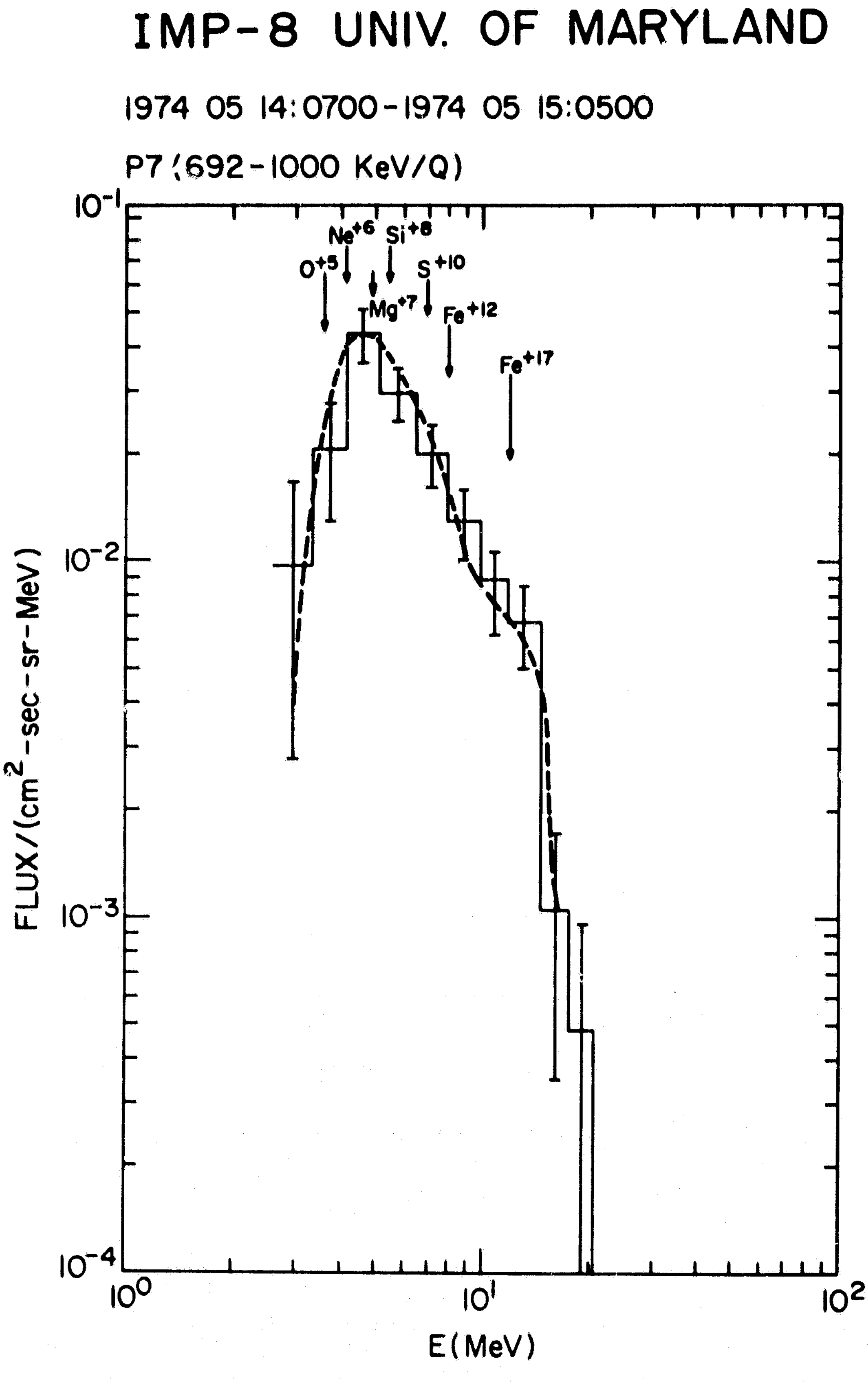


Figure 1

80-126



80-159

Figure 2