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EMISSION OF NEARLY STRIPPED CARBON AND OXYGEN FROM THE SUN

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and D. Hovestadt

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EMISSION OF NEARLY STRIPPED CARBON AND OXYGEN FROM THE SUN

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Received ______________

ABSTRACT

Energy spectra of nearly stripped carbon and oxygen nuclei observed during several solar particle events indicate a systematic deviation of these spectra from a simple power law: the spectra bend down below about 100 keV per nucleon and the degree of turn-over is highly correlated with the size of the flare, as measured by the "event averaged" flux of 130-220 keV protons. The energy spectra of helium computed for the same time periods do not show a similar feature. We find a large variability of the α/CNO ratio from event to event (from 2 to about 20 at 40 keV per nucleon), and in all cases examined the carbon and oxygen nuclei are nearly fully stripped. These results are interpreted as evidence for storage of energetic ions in hot ($T_e \sim 1.5 \times 10^{6}$ °K) coronal regions, followed by strong adiabatic deceleration.

Subject headings: Abundances, solar---cosmic rays---flares, solar

I. INTRODUCTION

The first measurements of the ionization states and energy spectra of solar particles extending to energies of $\sim$20 keV per nucleon have been reported recently by Sciambi et al. (1974). These results indicated that in one moderate-sized solar particle event examined (4-8 July 1974) low energy carbon and oxygen ions were nearly fully stripped and that their spectra deviated significantly from a simple power law in kinetic energy. In this paper, we describe the results of analysis of eight additional events, and conclude that the large degree of ionization and turn-over in the spectra are consistent features of low energy solar CNO ions. We examine the roles that coronal storage and interplanetary propagation might have in producing the observed spectra.

II. INSTRUMENTATION AND DATA ANALYSIS

The University of Maryland experiment aboard the earth-orbiting spacecraft IMP-8 (Explorer 50) is an electrostatic deflection sensor (Tums et al., 1974). A simplified cross-sectional view of the instrument is shown in Figure 1. An ion entering the instrument has its entrance trajectory defined by a collimator. The particle then enters one of three electrostatic field regions where its path is deflected by an amount inversely proportional to its kinetic energy per charge. On exit from the deflection cavity, the ion strikes one of an array of eight rectangular solid state detectors, each of which covers a well-defined deflection, and hence energy per charge, range. Pulse-height analysis of the detector signal allows a direct measurement of the particle's total energy, from which its charge may be determined. In addition, by using multiple energy thresholds on signals of several detectors, twelve counting rates having well-defined energy limits and hence charge responses are generated with time resolutions as short as five seconds. Nine of these rates are sectored into four directional quadrants in the ecliptic plane, providing data on particle anisotropies. Solid-state anticoincidence detectors, placed behind the detector array, and a plastic scintillator anticoincidence cup prevent analysis of penetrating particles. The energy ranges and charge responses of the various detectors are shown in Table I.

Background correction of a detector's pulse-height histogram is performed by subtracting a normalized histogram obtained from the same detector during quiet times, when the counting rates are at their lowest values. One of the solid-state detectors (P5) in the detector array is covered by a thin metal foil which stops deflected particles. It thus serves as a background monitor which, when pulse-height analyzed, identifies any changes in the shape of the background with time. Analysis of pulse-height histograms of this background detector shows that during quiet times all of the other detectors respond primarily to the secondary electron background produced in the spacecraft.

The relative abundance of individual charge states may be determined by fitting computed instrument response curves to the observed pulse-height distributions. The sensor is capable of fully resolving ionic charge states 1 to 4 for elements up to oxygen. In addition, charge states 5 to 8 are separated sufficiently so that, by means of a simple iteration procedure, abundances of these individual states may also be determined. Complete charge state identification for carbon and oxygen down to about 40 keV per charge is thus obtained. Of course, the individual elements may not be resolved in this manner since only the ionic charge (as opposed to nuclear charge) is determined. In many cases, however, the ions may be completely identified (i.e., ionic charge and nuclear charge) by using the simultaneous nuclear abundance information provided by the ULET, a thin-window proportional counter dE/dX *vs* E telescope (Hovestadt and Vollmer, 1971) of the Maryland/Max-Planck-Institut experiment.

Figure 2a shows a typical uncorrected pulse-height spectrum (histogram) obtained during the solar flare particle event of 1974 June 22. The measured smoothed background distribution is shown as a dashed line, and the histogram after background correction is shown in Figure 2b. This particular histogram was obtained from detector P3, which responds to ions in the energy range 130 to 220 keV per charge. The triple-peaked shape of the histogram is characteristic of every event which we have studied to date. The two left-hand peaks are produced by protons and alpha particles respectively, while the right-hand peak is due to particles having ionic charge 5-8 for C and O, and $8 \le Q \le 12$ for iron. The apparent energy per charge range for iron is lower because for low energy iron the energy measured in a solid-state detector is considerably less than its incident energy (Campbell and Lin, 1973). The large dip between the alpha peak and the Q = 5-8 peak is statistically consistent with a complete absence of ionic charges 3 and 4. In no event which we have examined have we ever seen evidence for the presence of these two charge states.

III. OBSERVATIONS

Our observations of low energy particles produced in the series of flares beginning on 1974 July 4 have been reported earlier (Sciambi *et al*., 1974). We summarize the results of our analysis of that event: (1) Rate data for 15-600 keV per nucleon ions heavier than helium indicate a strong bend-down in the energy spectra below 100 keV per nucleon, even late in the event, which cannot be attributed to velocity dispersion; (2) the proton and helium spectra show no such bending within the energy range of our detectors ($\gtrsim$ 130 keV for protons and $\gtrsim$ 40 keV per nucleon for alphas); (3) pulse-height analysis data support the observations listed above, and indicate that carbon and oxygen are almost fully stripped, having mean charge states of 5.5 and 7.2, respectively; and (4) the average α/CNO ratio for the event, as determined from PHA data, is about 16.

We have investigated a total of eight additional solar particle events observed by IMP-8 since its launch in late 1973. These data indicate that the features of the CNO spectrum in the July event were not unusual. In Figure 3, for example, we show proton, helium, and CNO spectra averaged over the time period 1974 June 10 0^h to June 12 0^h. This event, associated with a small solar flare on June 8, is typical in that the CNO spectrum flattens at low energies. The one unusual feature of this event (as compared with the other eight examined) is that the helium also seems to show a flattening; in fact, this is the only case in which we have seen such an effect in the alphas.

Figure 4 shows the time variation of the spectra index γ ($J \sim E^{-\gamma}$) for heavy ions between 20 and 40 keV per nucleon during the 10 June event. The effect of velocity dispersion is evident up to the beginning of day 162, at which time the spectral index settles down to a low, more-or-less constant value and remains at that value to the end of the event. The bend-over in the spectrum (low spectral index) cannot, therefore, be attributed to simple velocity dispersion.

Using the arrival times of the low energy heavy ions of various energies, it is possible to calculate their diffusion coefficients, κ, based on travel distances (along the average spiral magnetic field) of 1.2 AU. We obtain values of κ of between 4×10^{20} and 6×10^{20} cm^2 per sec, for ions with energies between 20 to 250 keV per nucleon. The very small ($<<3\%$) residual anisotropies which we observe after correcting for the Compton-Getting effect (Ipavich, 1974) are consistent with this low value of the diffusion coefficient.

Table 2 summarizes the observations for the nine particle events, all of which are associated with solar flares in the western limb of the sun. Four of these events show an "unusually low" spectral index ($\gamma < 1$) at low energies for CNO, while, with the exception of the June 10 event, none show a clear alpha turndown. We must caution, however, that since for alpha particles the low energy limit of our observations is 40 keV per nucleon, a factor of two higher than the lowest heavy ion energy, the possibility of an alpha turndown <u>below</u> 40 keV per nucleon cannot be ruled out. On the other hand, one can definitely say that if a turndown is present in the alpha spectra, it is not nearly as strong as for the case of the heavy ions. Elemental abundance information from ULET indicates that for the nine events observed, the abundance of nitrogen relative to (carbon and oxygen) was $<10\%$ at 500 keV per nucleon for each of the cases examined. It is therefore reasonable to assume that very little nitrogen is present at the lower energies as well, and we are thus able to make determinations of the ionization states of carbon and oxygen. We find that in <u>all</u> events the ionization states of carbon and oxygen are about 90% of the nuclear charge, i.e., these ions are nearly fully stripped. The α/CNO ratio at 40 keV per nucleon shows a great variability from event to event, but there is no correlation of CNO abundance with the degree of turndown in the spectra; nor is there a correlation with helium flux, CNO flux, or location of the flare. There is, however, a strong correlation of CNO spectral index γ_{CNO} with the low energy (≤ 150 keV) proton flux averaged over the event. This interesting correlation is evident from Figure 5, where we plot the CNO spectral index from 40-80 keV per charge vs the "event averaged" 130-220 keV proton flux. The trend is clear: the larger the flare as measured by the low energy proton flux, the stronger the bend in the spectrum.

IV. DISCUSSION

After passage through a sufficient amount of "cold" matter, the charge states of ions approach limiting values Q* given by the semi-empirical relation (Betz, 1972)

$$Q^* = Z[1 - 1.032 \exp(-137\beta/Z^{.69})]$$

where Z is the atomic number and βc the velocity of the ions. For the energies observed by us, Q* is computed to be about 2.5 carbon and 2.9 for oxygen. These numbers are clearly inconsistent with our results.

The heavy ions we observe may have been stripped through impact ionization by keV electrons produced in the flash phase of the flare, as suggested by Braddy et al (1973). However, the charge states, while high, do not indicate complete stripping, as we would expect if this mechanism were the dominant one.

We note that from the work of Jordan (1969) and others (Allen and Dupree, 1967; Lange and Scherb, 1970) the ionization states observed are consistent with those expected for ions in thermal equilibrium with an electron gas at a temperature of 1-2 x 10^{6}°K. In addition, the charge states are very similar to those observed in the solar wind (Bame *et al.*, 1970). We thus suggest that the low energy heavy ions seen near earth have achieved charge state equilibrium in regions of the solar corona from which the solar wind originates.

We now address the question of what causes the observed turndown in the CNO spectrum. The first possibility which comes to mind is the effect of ionization energy loss in the spectra during propagation from the acceleration region, and/or storage in the corona. In this case it is important to use the correct form of the energy loss equation for low particle energies. The most commonly used form, $dE/dx \sim 1/E$, breaks down as the particle velocity approaches the electron thermal velocity (v_{the}). For an electron temperature of $\sim 10^{6}$°K, this corresponds to a particle energy of ∿225 keV per nucleon. The problem of the slowing down of an ion in a fully ionized plasma has been treated by several authors. We shall use the results of Itikawa and Aono (1965), who find a form of the energy loss equation which is valid for all values of the ion velocity:

$$\frac{dE_i}{dx} = -1.512 \times 10^{-12} \frac{n_e}{T_e} \frac{Q^2}{M_i} \left\{ \ln \left(\frac{T_e{}^3}{n_e Q^2} \right)^{1/2} + 9.13 \right\} \left\{ \frac{\mathrm{erf}(u)}{u^2} - 1.129 \frac{\exp(-u^2)}{u} \right\} \tag{1}$$

with $u = 79.5 \sqrt{E_i/T_e}$, where E_i is the ion energy in keV per nucleon, T_e is the electron temperature of the medium in °K, M_i is the ion mass in AMU, x is the path length in cm, n_e is the electron density of the medium in cm^{-3} and erf is the normal error function: $\mathrm{erf}(u) = \frac{2}{\sqrt{\pi}} \int_0^u \exp(-x^2)\,dx$.

In the low energy limit ($v_{ion} << v_{the}$) the specific energy loss, dE/dx is proportional to v_{ion} or $\sqrt{E_i}$, while in the high energy limit

($v_{ion} >> v_{the}$), $dE/dx \sim 1/E_i$. We assume that the particles were initially accelerated to a power law spectrum in kinetic energy, $J(E) = J_0E^{-\gamma}$, and ask what effect ionization loss could have on the spectrum.

It can be shown (Ipavich and Sciambi, in preparation) that propagation of all particles through the same amount of material causes the spectral index, for low energies, to approach a limiting value of 1/2, regardless of the input spectral index. Since for some events there is evidence that γ is less than 1/2, we look to a combination of propagation and storage to produce the observed effect.

In Figure 6 we show numerical integrations of equation (1) for various ions, for an initial power law spectrum $J(E) \sim E^{-3}$, propagated outward from an injection point at 1.2 $R_\odot$ to a storage area at 2 $R_\odot$, stored at 2 $R_\odot$ for 10 hours, and then propagated out to earth. The corona has been assumed to be isothermal, with an electron temperature of 1.5×10^{6} °K. The particular values of the storage radius and time do not affect the limiting slopes of the curves in Figure 6, only how quickly these limits are reached. The factor Q^2/M in equation (1) is apparent in the difference in degree of flattening for alphas and heavier nuclei. Clearly a "kink" occurs in the spectrum. However, it is at an energy about ten times higher than observed (see Figure 3). In addition, the energy spectra of both alphas and protons should also show a bend-over, a feature which is not evident in the data.

The energy at which the bend occurs is, to first order, a function only of the parameter u in equation (1), or of E_i/T_e. In order to make the calculated spectra consistent with observation, the bend energy must be lowered by about a factor of 10. This can be accomplished by lowering the temperature of the storage by a factor of 10. But from the observed charge states of the ions we may put limits on the temperature of the storage region. Specifically, from the upper limits of the abundance of C^{+4} observed, the storage temperature must have been greater than 8×10^5°K (Jordan, 1969), far too high to produce the flattening at the observed energy. We may also rule out storage at low temperatures (with low equilibrium charge states) followed by stripping for the following reason: A turndown in the spectra of CNO which is more pronounced than for alphas, requires that in the storage region the parameters $\frac{Q^2}{M}$ in equation (1) must have been greater for CNO than for alphas. Since for alphas, $\frac{Q^2}{M} = 1$, $Q^2 > 12$, or $Q > 3.5$ for carbon, which implies that in order for these high charge states to be maintained, the temperature in the storage regions must again have been $> 8 \times 10^5$°K. Therefore, we argue that coronal propagation and storage alone could not have produced the spectral flattening at the energies where we observe it.

Verzariu and Krimigis (1972) have pointed out that by allowing the diffusion coefficient κ to depend on particle velocity, a bend in the spectrum can be produced by adiabatic deceleration. But, since the energy change mechanism would depend only on particle velocity, different species observed at the same velocity should have experienced identical propagation effects, and should have "mapped back" to the same source velocity. However, in the present case, the absence of a strong alpha turndown at the same kinetic energy per nucleon (or velocity) as for carbon and oxygen makes it unlikely that the bending is caused by a velocity-dependent κ. Using an identical argument, we rule out the effect of a rigidity-dependent diffusion coefficient, since by virtue of their high state of ionization the carbon and oxygen have nearly the same rigidity as the alphas at the same energy per nucleon. Adiabatic deceleration can certainly change the shape of the spectra: our point here is that this deceleration should produce identical changes in the spectra of all species observed.

We suggest that the observed bend in the spectra is caused in the following manner: particles (alphas and heavier nuclei) are accelerated in a source region to a power law spectrum in kinetic energy. The particles are then stored in a region of coronal temperatures ($T_e \sim 1.5 \times 10^6 {}^\circ K$), which may or may not be the same as the source region. This trapping region is probably within 3 $R_\odot$ of the solar surface (Anderson, 1972). Here the particles lose energy through ionization loss, their spectrum flattens at about 800 keV per nucleon and some of the ions are stripped of their outer electrons. From our observation of the observed correlation between the degree of flattening and the low energy proton flux, we conclude that the storage time is proportional to the "size" (i.e., total energy) of the flare. The particles are then diffusively propagated outward to the earth, losing energy by adiabatic deceleration. Here we assume that the diffusion coefficient is independent of particle parameters, so that the adiabatic deceleration does not affect the shape of the spectrum, but simply moves it to lower energies (Venkatarangan and Lanzerotti, 1975). Under these conditions, the required energy losses may be produced by a diffusion coefficient of the order of 5×10^{20} cm^2 sec^{-1} (Parker, 1965) which is consistent with our observations. Thus, the "bend" in the spectrum of CNO is moved down to the energy at which it is observed. Statistical errors in our helium observations prevent an unambiguous identification of the predicted bending in the helium spectra.

Because theoretical results derived for alpha particles apply equally for protons, there should also be a bend in the proton spectrum to match that of the alphas. Since the lowest observed energy for protons is even higher than that for alphas, we do not expect to see this bend. We also note that all species appearing in Figure 6 were initially equally abundant. After storage, the heavy ion abundances are depressed relative to helium. Thus, in order to explain events which show enhanced heavy element fluxes, it is necessary either to have a "super enriched" source, or to invoke some form of preferential acceleration.

Although we believe that we have proposed a reasonable mechanism for producing most of the observed features of the carbon and oxygen spectra, our conclusions at this point are tentative. Additional event statistics may shed further light on the relative contributions of coronal storage and energy losses in producing the observed charge states and spectra.

V. SUMMARY

In a total of nine solar particle events of various sizes we have observed a bend-down of the energy spectra of carbon and oxygen below 100 keV per nucleon. In addition we find that:

(a) In all events examined carbon and oxygen nuclei are nearly fully stripped; the observed ionization states are consistent with thermal equilibrium of these ions with the medium at a temperature of $\sim 10^6$ °K.

(b) There is a great variability from event to event in the α/CNO ratio at 40 keV per nucleon.

(c) There is, in all but one case, no clear helium bend-down.

(d) There is no apparent correlation of the degree of turndown in the CNO spectrum with the relative CNO abundance, the helium flux, the CNO flux, or the location of the flare.

(e) The amount of bending in the CNO spectrum is strongly correlated with the event-averaged flux of protons in the energy range 130-220 keV.

These observations are consistent with storage of an initial power law spectrum at coronal densities of $\sim 5 \times 10^6$ cm^{-3} and temperatures of $1\text{-}2 \times 10^6$ °K for $\sim$ 10 hours, followed by strong adiabatic deceleration.

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Table 1

Energy Ranges and Charge Responses for IMP-8 Detectors

Detector	**PHA Charge Threshold**	**Energy Range (keV per charge)**	**Rate**	
			Charge Thresholds	Sectored
P1	**$Q \geq 6$**	**37-55**	$Q \geq 6$	Yes
P2	**$Q \geq 2$**	**65-100**	$Q \geq 2$/$Q \geq 6$	Yes/No
P3	**$Q \geq 1$**	**130-220**	$Q \geq 1$	Yes
P4	**$Q \geq 1$**	**160-230**	$Q \geq 1$	No
P5	**background**	**$\gtrsim$160 keV**	---	Yes
P6	**$Q \geq 1$**	**390-600**	$Q \geq 1$/$Q \geq 6$	Yes/Yes
P7	**$Q \geq 1$**	**640-1100**	$Q \geq 1$/$Q \geq 2$	Yes/No
P8	**$Q \geq 1$**	**740-1200**	$Q \geq 1$	Yes
N	**electrons**	**600-800 keV**	---	Yes

Table 2

Characteristic of Nine Solar Flare Particle Events

Date	Relative Abundance α/CNO (40 keV/nuc)	Alpha Spectral Index γ_α 40-80 keV/nuc	CNO Spectral Index γ_{CNO} 20-40 keV/nuc	proton flux $(cm^2\text{-sr-sec-MeV})^{-1}$ 130-220 keV	Approximate Flare Location	Comments
11/4/73	14	1.9 ± 0.2	1.1 ± 0.4	340	S13W82	
1/25/74	17	2.4 ± 0.3	0.9 ± 0.5	1000	N09W60	
5/14/74	2	2.8 ± 0.4	2.4 ± 0.3	65	S13W66	"iron rich"(a)
5/31/74	17	2.6 ± 0.3	1.5 ± 0.4	100	S15W63	
6/10/74	3	0.4 ± 0.5	0.15 ± 0.5	1200	S13W64	alpha turndown
6/22/74	7	2.7 ± 0.4	2.0 ± 0.5	200	S20W27	
6/26/74	14	3.1 ± 0.5	1.1 ± 0.5	250	S14W70	
7/ 4/74	16	1.8 ± 0.3	-0.2 ± 0.5	12000	S16W08	
11/8/74	8	1.7 ± 0.2	-0.5 ± 0.75	2500	S12W85	

(a) Gloeckler et al., 1975

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Garching b. München, W-Germany

Figure Captions

Figure 1 -- Cross-sectional view of the University of Maryland electrostatic deflection sensor as flown on the IMP-8 spacecraft. The 15 solid state detectors are surrounded by a plastic scintillator anticoincidence. Six of the detectors (open rectangles) are used in an anticoincidence mode to prevent analysis of penetrating particles.

Figure 2 -- Typical pulse height histogram from the IMP-8 experiment, obtained from detector P3 during a solar particle event.

a) shows the histogram before correction for background (the smoothed background curve is shown as a dashed line).

b) show the histogram after subtraction of background. Note the three-peaked form of the corrected histogram.

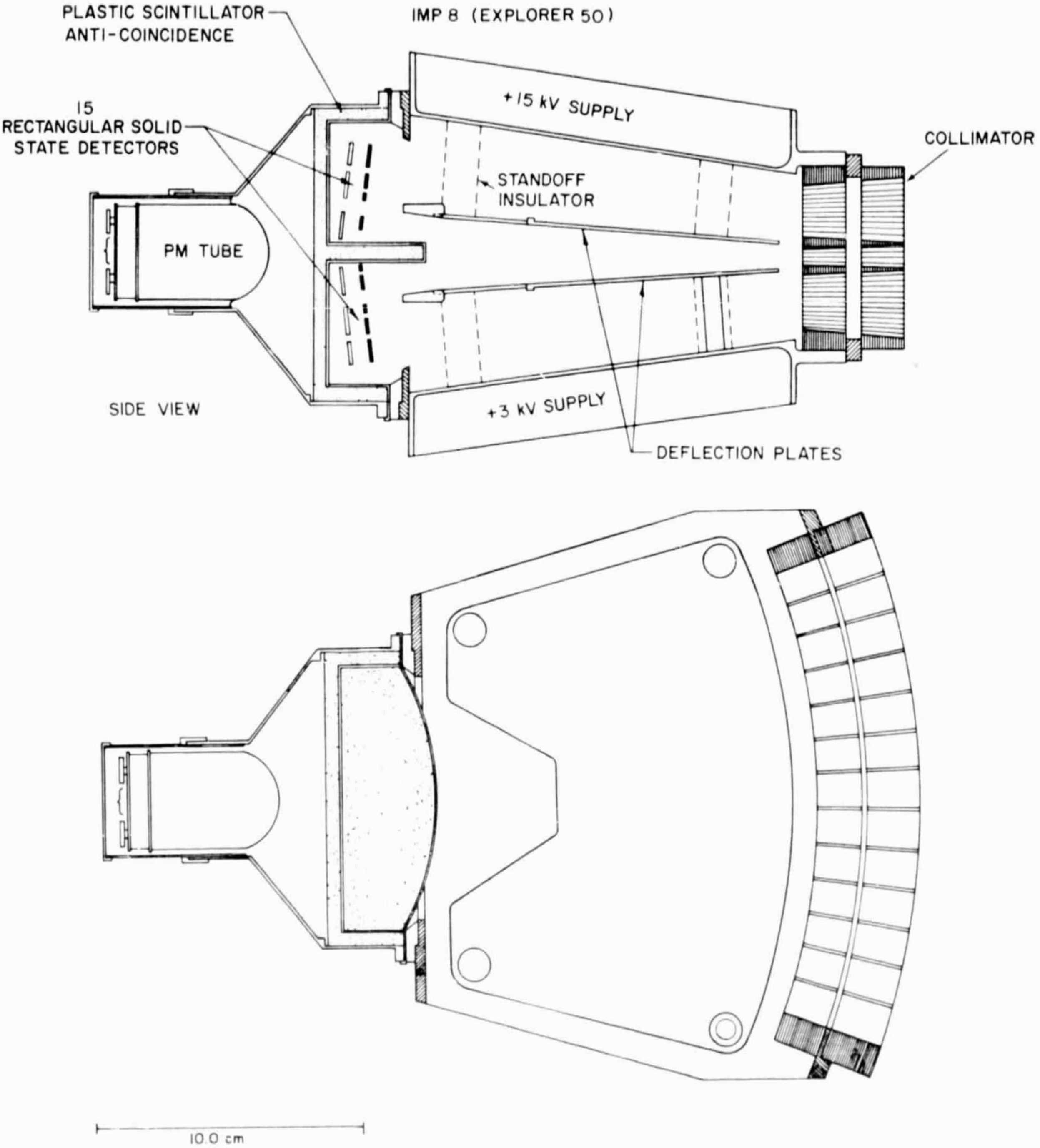
Figure 3 -- Proton, helium, and CNO group energy spectra in the 10 June 1974 event.

Figure 4 -- CNO spectral index (40-80 keV per charge) vs time for the 10 June 1974 event.

Figure 5 -- CNO spectral index (40-80 keV per charge) vs "event-averaged" proton flux (130-220 kev) for the nine particle events observed. Note the strong correlation with event size.

Figure 6 -- Calculated in differential spectra after coronal storage. The curves were obtained by numerically integrating equation (1) outward from the injection point. The straight line J_o is the injection spectrum for all species.

ELECTROSTATIC ENERGY - CHARGE ANALYZER
UNIVERSITY OF MARYLAND
IMP 8 (EXPLORER 50)



ELECTROSTATIC ENERGY/CHARGE ANALYZER
CROSS SECTION - TOP VIEW

FIGURE 1

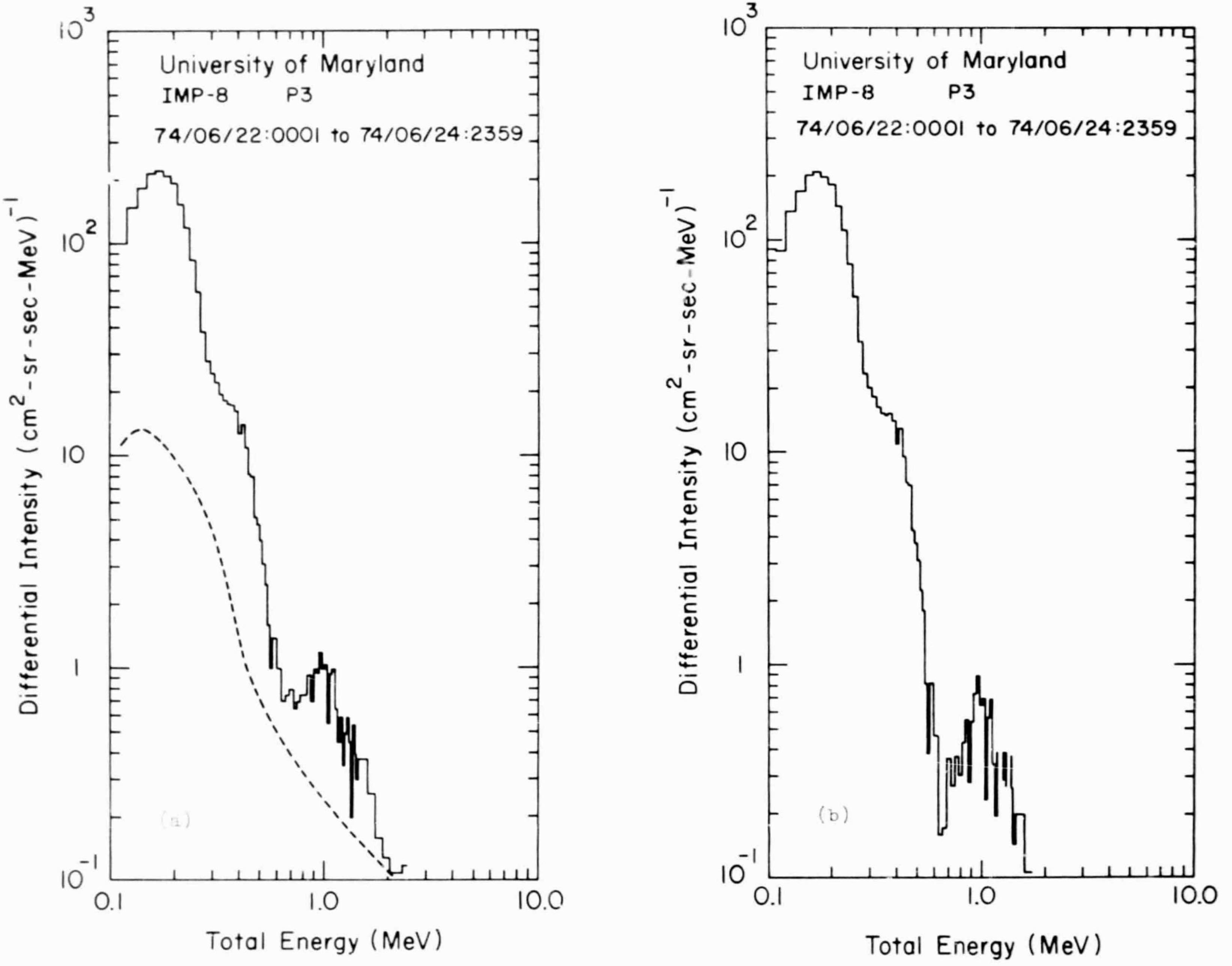

University of Maryland
IMP-8 P3
74/06/22:0001 to 74/06/24:2359
Differential Intensity $(cm^2$-sr-sec-MeV$)^{-1}$
10^3
10^2
10
1
10^{-1}
0.1
1.0
10.0
Total Energy (MeV)
(a)
(b)

FIGURE 2

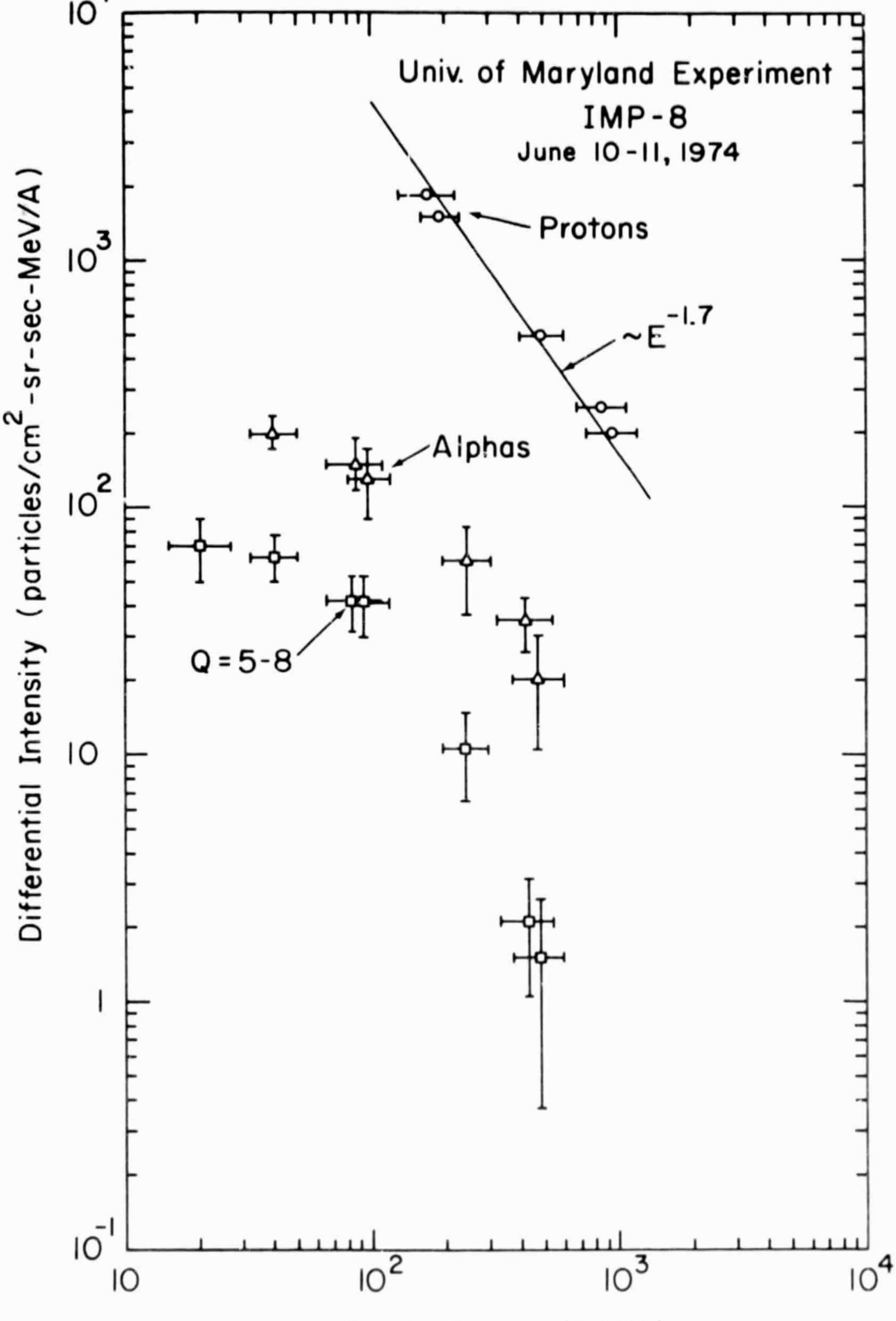

Univ. of Maryland Experiment
IMP-8
June 10-11, 1974
Protons
$\sim E^{-1.7}$
Alphas
Q = 5-8
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
Differential Intensity (particles/cm^2-sr-sec-MeV/A)
10
10^{2}
10^{3}
10^{4}
Kinetic Energy (keV/A)

FIGURE 3

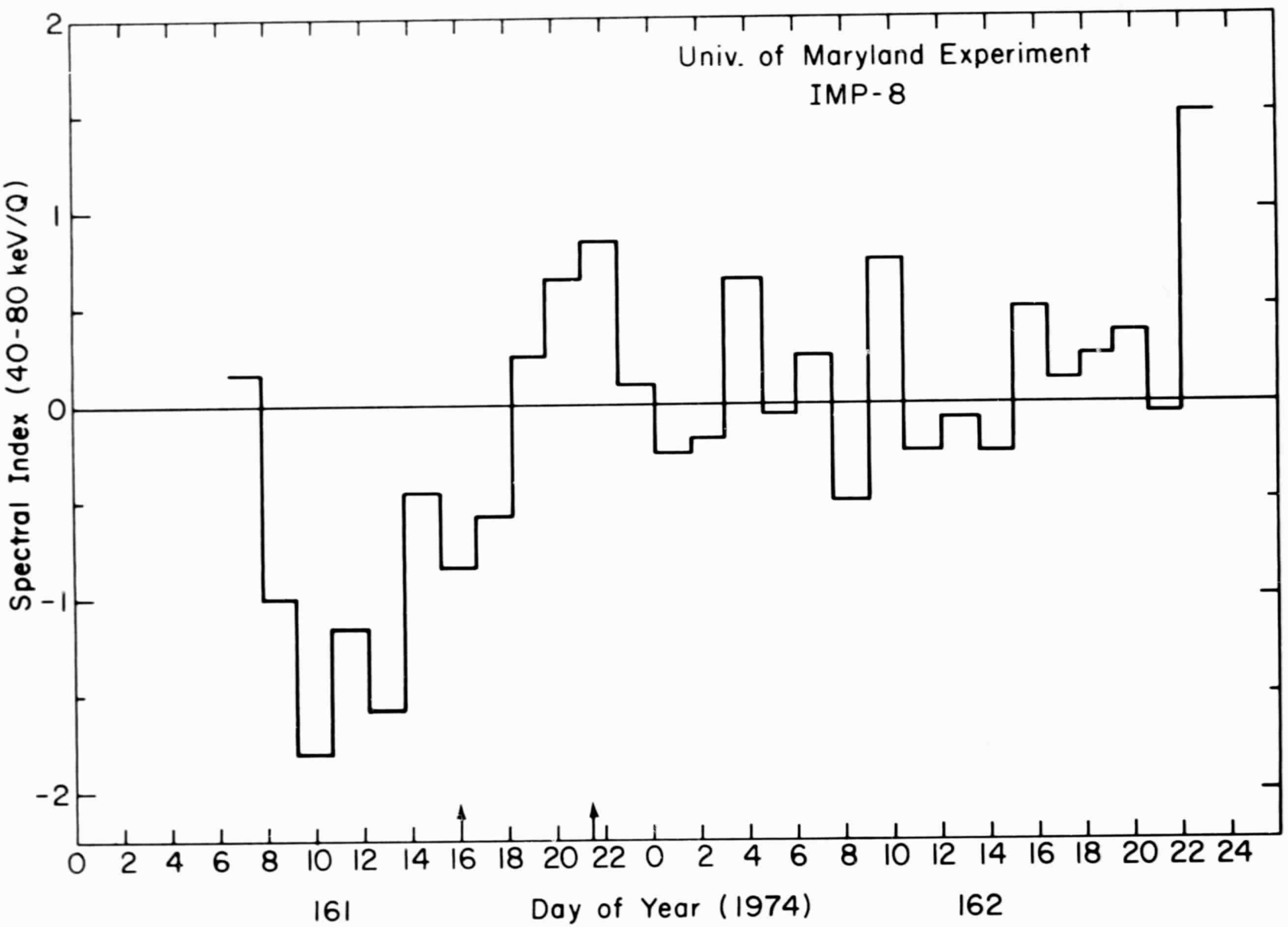

Univ. of Maryland Experiment
IMP-8
Spectral Index (40-80 keV/Q)
2
1
0
-1
-2
0
2
4
6
8
10
12
14
16
18
20
22
0
2
4
6
8
10
12
14
16
18
20
22
24
161
Day of Year (1974)
162

FIGURE 4

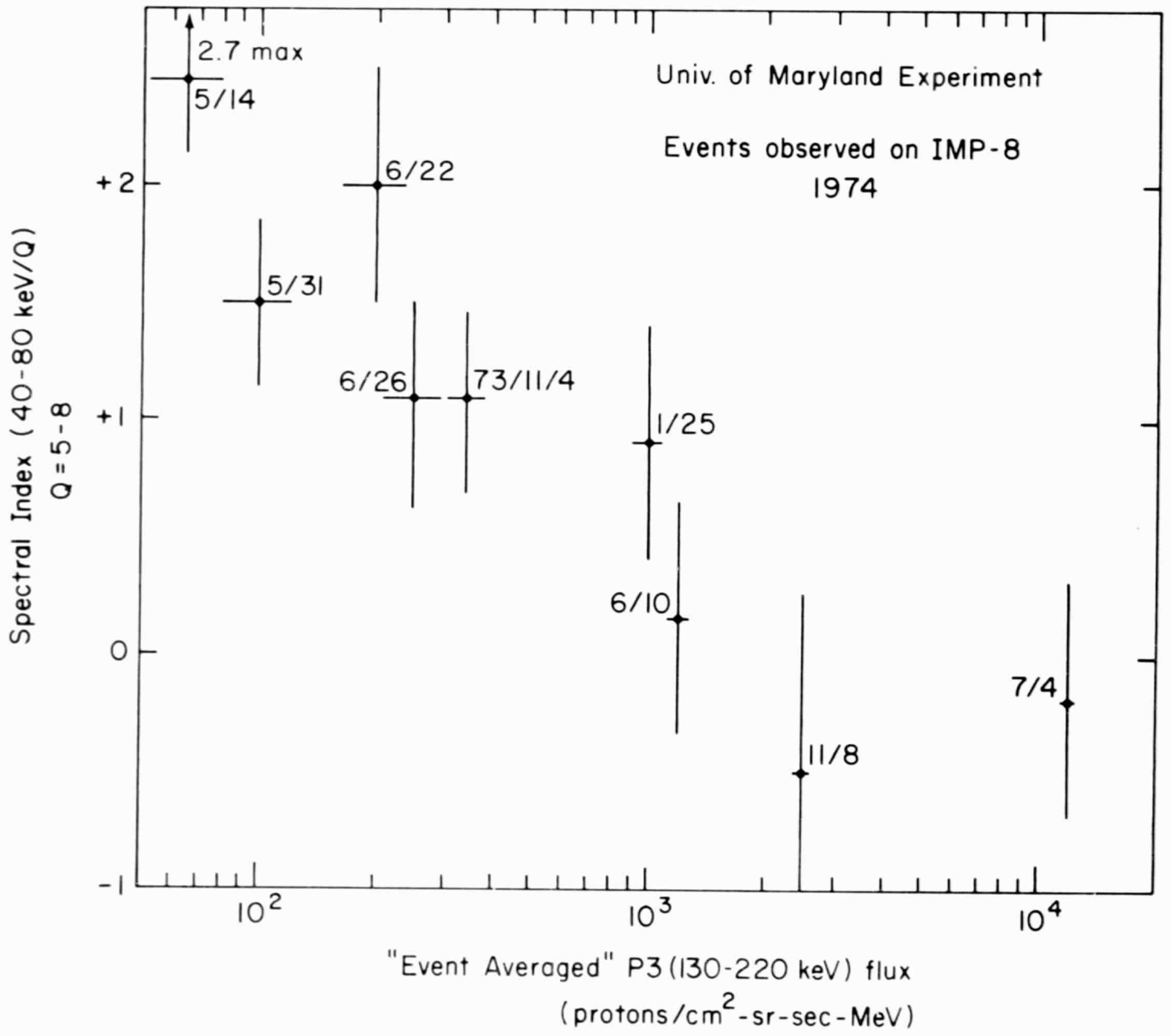
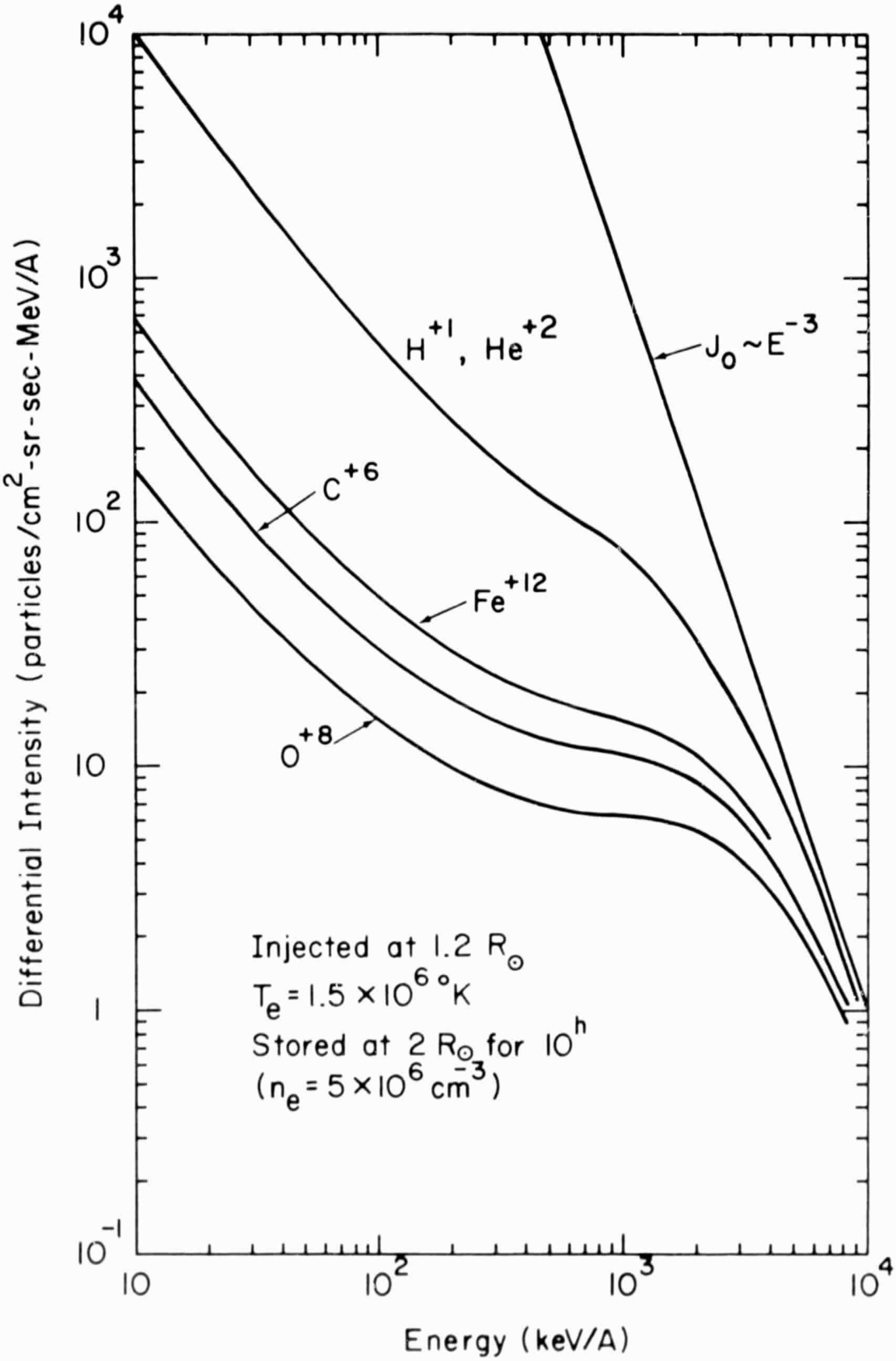

2.7 max
5/14
Univ. of Maryland Experiment
Events observed on IMP-8
1974
6/22
5/31
6/26
73/11/4
1/25
6/10
11/8
7/4
+2
+1
0
-1
Spectral Index (40-80 keV/Q)
Q = 5-8
10^2
10^3
10^4
"Event Averaged" P3 (130-220 keV) flux
(protons/cm^2-sr-sec-MeV)

FIGURE 5



10^4
10^3
10^2
10
1
10^{-1}
Differential Intensity (particles/cm^2-sr-sec-MeV/A)
H^{+1}, He^{+2}
$J_0 \sim E^{-3}$
C^{+6}
Fe^{+12}
O^{+8}
Injected at 1.2 $R_\odot$
$T_e = 1.5 \times 10^6$ °K
Stored at 2 $R_\odot$ for 10^h
($n_e = 5 \times 10^6$ cm^{-3})
10
10^2
10^3
10^4
Energy (keV/A)

FIGURE 6