TIME DISPERSION OF ENERGETIC SOLAR PARTICLES: UNEXPECTED VELOCITY AND SPECIES DEPENDENCE

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Technical Report # 76-114
Physics Publication # 76-260

May 1976

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

TIME DISPERSION OF ENERGETIC SOLAR PARTICLES: UNEXPECTED VELOCITY AND SPECIES DEPENDENCE

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ABSTRACT

The intensity-time behavior for protons and helium, as well as for carbon, oxygen and iron ions has been measured following the 1974 September 19 solar flare for energies between 0.5 and $\sim$ 5 MeV per nucleon. The profiles display a time dispersion which is inversely proportional to velocity for each individual species. In addition, at a given velocity the time dispersion also depends on the charge to mass ratio of the ion. Based on this latter dependence, it is concluded that while carbon and oxygen are essentially fully stripped iron nuclei are not, having an effective charge $Q = 10 \pm 5$. The observed dispersion cannot be explained by purely rigidity dependent diffusive propagation.

Subject Headings: energetic solar particles - interplanetary propagation - composition and energy spectra

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I. INTRODUCTION

Recent studies of the relative abundance of elements in solar cosmic rays have revealed large enhancements of heavy nuclei at low energies with respect to nominal solar abundances (Price et al. 1973; Braddy et al. 1973; Crawford et al. 1975; Gloeckler et al. 1975a; Hovestadt et al. 1975) which show large variations from event to event (Mogro-Campero and Simpson 1972; Gloeckler 1975). In addition, the results of Van Allen et al. (1974), and Armstrong et al. (1976) suggest that the abundance of $Z \geq 3$ nuclei relative to helium varies significantly during individual events. Such results have made it clear that a better knowledge of propagation effects and associated biases is necessary before the full potential of such work for the understanding of important physical properties of the solar corona can be realized.

In this Letter we report the results of the first detailed study of the intensity-time profiles for individual heavy ion species following a solar flare. The observations permit the analysis of the propagation behavior of heavy ions in a way heretofore only possible for protons and alpha particles, and allow the time-evolution of the spectra and relative abundances of the individual chemical elements to be examined.

The measurements were conducted with the ULET sensor of the University of Maryland/Max-Planck-Institut experiment on the IMP 8 earth orbiting spacecraft. This instrument, described in more detail elsewhere (Gloeckler et al, 1975a; Hovestadt et al, 1973; Hovestadt and Vollmer, 1971) uses a thin-window gas flow - through proportional counter to measure energy-loss (dE/dx) and a solid-state detector to measure the residual energy (E) for stopping particles. It provides a two parameter matrix analysis from which the nuclear charge and energy of a particle can be determined over the energy range from less than 0.3 to more than 5 MeV per nucleon.

The solar event we have selected for the first detailed analysis is the result of an importance 2N flare which occurred at 2250 UT 1974 September 19 at W62. The location of this flare lies roughly in the middle of the so-called "preferred-connection region" (Van Hollebeke et al, 1975) or "fast propagation region" (Reinhard and Wibberenz, 1974) so that the effects of coronal propagation should not be significant.

II. OBSERVATIONS

Selected intensity versus time profiles for individual nuclei in narrowly defined energy per nucleon intervals are displayed in Figure 1. The data are plotted as short horizontal segments, each of which represents the particle flux determined from the appropriate portion of the corresponding "track" on a dE/dx by E pulse height matrix accumulated over a 3 hour interval. The flux is corrected for analyzer dead-time using the triggering rate of all events satisfying the matrix logic condition. Each three hour flux segment is connected to the next by an oblique segment representing a three hour gap during which the event acceptance threshold was lowered, and protons and helium nuclei were measured. The smooth asymmetric curve drawn through each flux vs. time data set is characterized by only three parameters, amplitude, rise time and decay time, and is fitted to the data by the method of least squares. The three parameters derived from such fits have been used in the subsequent analysis.

These and similar profiles for other energies and species are characteristic of diffusive propagation following impulsive injection, that is, a relatively rapid rise to a maximum followed by a more gradual decay over a period of 50 to 60 hours. Two distinct dispersive effects are clearly evident. First, the dispersion in time to maximum for

oxygen at two different energies, 0.6 - 1.0 and 3.4 to 4.6 MeV per nucleon, shown in Figure 1(a), illustrates the way in which the spectrum is continually evolving due to velocity dispersion. A second, unexpected effect is the dispersion between two different nuclei at the same velocity (same energy per nucleon interval) as seen in Figure 1(b). Oxygen takes between 6 and 10 hours longer than the iron to reach maximum intensity. We note also that the relative abundance of iron to oxygen (as well as the spectra of individual species) is varying systematically with time and it is thus clear that a "snapshot" measurement of the relative abundances, particularly during the onset phase, could give misleading results.

III. ENERGY SPECTRA AND RELATIVE ABUNDANCES

The most common procedure for determining spectra and relative abundances of solar particles is to integrate observed fluxes over some portion of the period of the intensity increase, generally the entire increase. As an alternative to this usual approach we have used the maximum amplitude of each intensity vs. time profiles to construct the energy and abundance spectra. The resulting differential energy spectra for C, O, and Fe nuclei are shown in Figure 2 (solid symbols). We find that the energy spectra measured in this way are less steep than the spectra integrated over the entire particle event. For example, the time-averaged oxygen spectrum, shown for reference (open circles) in Figure 2, can be characterized by a spectral index of 2.4 ± 0.2 as compared with 1.8 ± 0.2 for the spectrum of peak intensities. In contrast to the noted differences in the energy spectra, we find that the differences in the relative abundance spectra resulting from the two approaches are not significant. Inset in Figure 2 is a plot of the C/O and Fe/O ratios as a function of energy determined from the peak intensities.

Both this method and the ratios from the time integrated profiles show that C/O have roughly the same spectrum but that Fe/O is enhanced at lower energies. This clearly illustrates that the iron enhancement seen here [as well as reported previously at these energies by Braddy et al. 1973 and Crawford et al. 1975, although not universally observed (Hovestadt et al. 1973)] cannot be due to a propagation bias. We note in passing that a "snapshot" measurement during the onset phase would have yielded a further enhancement that would be due to a propagation bias.

IV. ANALYSIS OF DISPERSIVE EFFECTS

To carry out a quantiative analysis of dispersive propagation effects, we have determined τ_m, the time of maximum intensity for each of the fitted curves for protons, helium, oxygen, carbon and iron. The uncertainty in the determination of τ_m was calculated from the uncertainties in the parameters of the fitted curve and was typically found to be $\sim \pm$ 3 hours (see also Figure 1). For each species the time of maximum was determined for at least 5 and as many as 13 energy intervals.

The times to maximum are plotted separately for each species as a function of $\beta = v/c$ (here v is the particle velocity) in Figure 3. Typical error bars are shown. From the figure it is evident that the times to maximum for each individual ion type are consistent with what would be expected for a pure velocity dispersion. Such a dispersion has been known to be a characteristic of the behavior of many solar proton events (Bryant et al. 1965; Reinhard and Wibberenz, 1974). We find that a least square fit to determine the exponent of an assumed dependence of the form $\tau_m \propto \beta^{-n}$ yields values for n which lie between 0.85 and 1.15 in all cases. The constancy of the product $v\tau_m$ for a

given species implies that the most probable "distance traveled" by that ion species does not depend on particle momentum. A surprising feature evident from Figure 3 is that the characteristic distances traveled ($v\tau_m$) are different for different species, falling roughly into three groups: a) protons, b) helium, carbon and oxygen, and c) iron. These characteristic distances are indicated in Figure 3.

Two distinct conclusions follow:

(1) The dispersion in the time to maximum for different species at the same velocity is some function of the charge to mass ratio, Q/A and

(2) The dispersion appears to depend primarily on Q/A and only weakly or not at all on magnetic rigidity $P(\propto \frac{A}{Q} v)$, since the individual species show no obvious dependence of the distance traveled on momentum.

V. DISCUSSION

It is a simple matter to apply the feature stated in conclusion (1) above to estimate the iron charge states which can not otherwise be measured in this energy range at the present time. Assuming only that helium nuclei are fully ionized we conclude that both carbon and oxygen nuclei are also essentially fully stripped since they exhibit within errors, the same time dispersion as the helium. This is consistent with the conclusions of Gloeckler et al. (1973, 1975b) based on direct measurements of the charge states of these ions at lower energies. Furthermore, we conclude unambiguously that iron is only partially stripped. If we take A/Q = 1 for protons, A/Q = 2 for the He, C, and O and assume $v\tau_m \propto (A/Q)^{-\alpha}$ we find from the data of Figure 3 that $\alpha = 0.45 \pm 0.12$. The charge states for iron which would make the observed times consistent with this relation are those with $Q_{Fe} = 10 \pm 5$ and are similar to the mean charge state of low energy iron measured

directly to be 11.6 in the 1974 May 14-15 iron rich particle by Gloeckler et al. (1976). On the other hand, this is in contrast with the conclusion reached by Sullivan and Price (1973) using indirect arguments that iron nuclei in a solar flare event were fully stripped at about 2 MeV per nucleon.

With regard to the second conclusion above we note that it is difficult to see how a general propagation theory can explain the species dependent splitting as a rigidity dependent effect without also introducing some momentum dependent component in the 'distance traveled" by each species. Diffusion theory predicts that $\tau_m \propto 1/K$ and in general that the diffusion coefficient $K \propto \beta f(P)$ where $f(P)$ is some function of the particle magnetic rigidity P. This function is in turn related to the resonance of the particle cyclotron radius r_c with the spatial irregularities in the interplanetary magnetic field. One possible explanation of the discrepancy is that at the "microscopic" level, the effective diffusion coefficient has a component which depends on cyclotron frequency, $\omega_c (\propto Q/A)$, and not on cyclotron radius, $r_c (\propto P)$. A less exotic explanation has been offered by M. Scholer (private communication) who has carried out Monte Carlo simulation of the entire propagation process which shows that adiabatic energy loss effects can weaken the dependence of the time to maximum on energy. Thus it is possible that a rigidity dependent diffusion could cause a species splitting depending on Q/A while the effects of adiabatic deceleration (which certainly cannot be neglected at these energies) distort the resulting energy dependence of the time to maximum so that an apparent pure velocity dispersion results. A search for similar dispersive effects at higher energies (proton and helium observations alone would be sufficient), where adiabatic energy losses are less important, would be helpful in deciding among the two possibilities.

We particularly wish to thank Dr. M. Scholer for many illuminating discussions in the course of this analysis. One of us (J. O'G.) acknowledges the support of the Alexander von Humboldt foundation while this research was carried out and also expresses thanks to all at the Max-Planck-Institut für extraterrestrische Physik for their generous hospitality during his stay. We are also grateful to Dr. O. Ullmer for his essential efforts in the basic design and development of the experiment and to P. Leaverenz, E. Künneth, E. Tums and J. Cain for their contributions to the successful operation of the instrument. This work was supported by NASA under Contract NAS 5-11062, grant NGR 21-002-316 and by the German Government.

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FIGURE CAPTIONS

Fig. 1(a) -- Intensity vs. time profiles for oxygen nuclei at two different energies. Each smooth curve is a 3 parameter function fit to the data by a method of least squares.

Fig. 1(b) -- Intensity vs. time profile for 0.6 - 1.0 MeV/nucleon ions of oxygen and iron (same velocity). The smooth curves are fits to the data. The earlier arrival of iron can only be explained if it has retained a substantial fraction of its atomic electrons. Note also that this effect can bias abundance ratios measured during the onset phase.

Figure 2 -- Differential energy spectra constructed from the maximum intensity of the corresponding fitted profile at each energy for oxygen, carbon and iron. For comparison, the oxygen spectrum averaged over the whole profile (open circles) is also shown. The inset figure shows the abundance of carbon and iron relative to oxygen measured at the maximum of each of the respective profiles.

Figure 3 -- The time of maximum of the respective fitted profiles as a function of particle velocity. The individual species are consistent with a pure velocity dispersion (β^{-1}) but there is a species splitting which depends on and provides a measure of the charge to mass ratio.

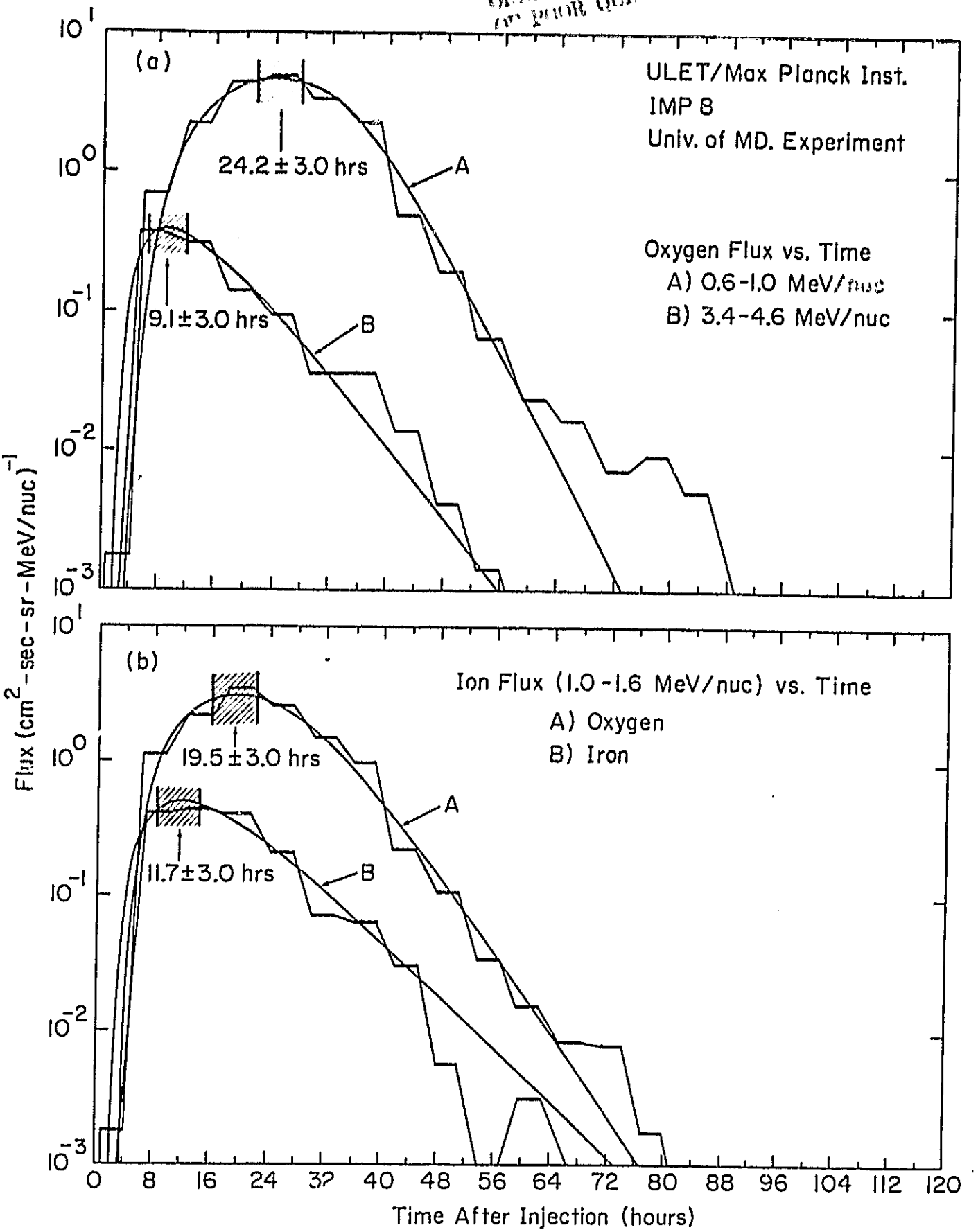

FIGURE 1

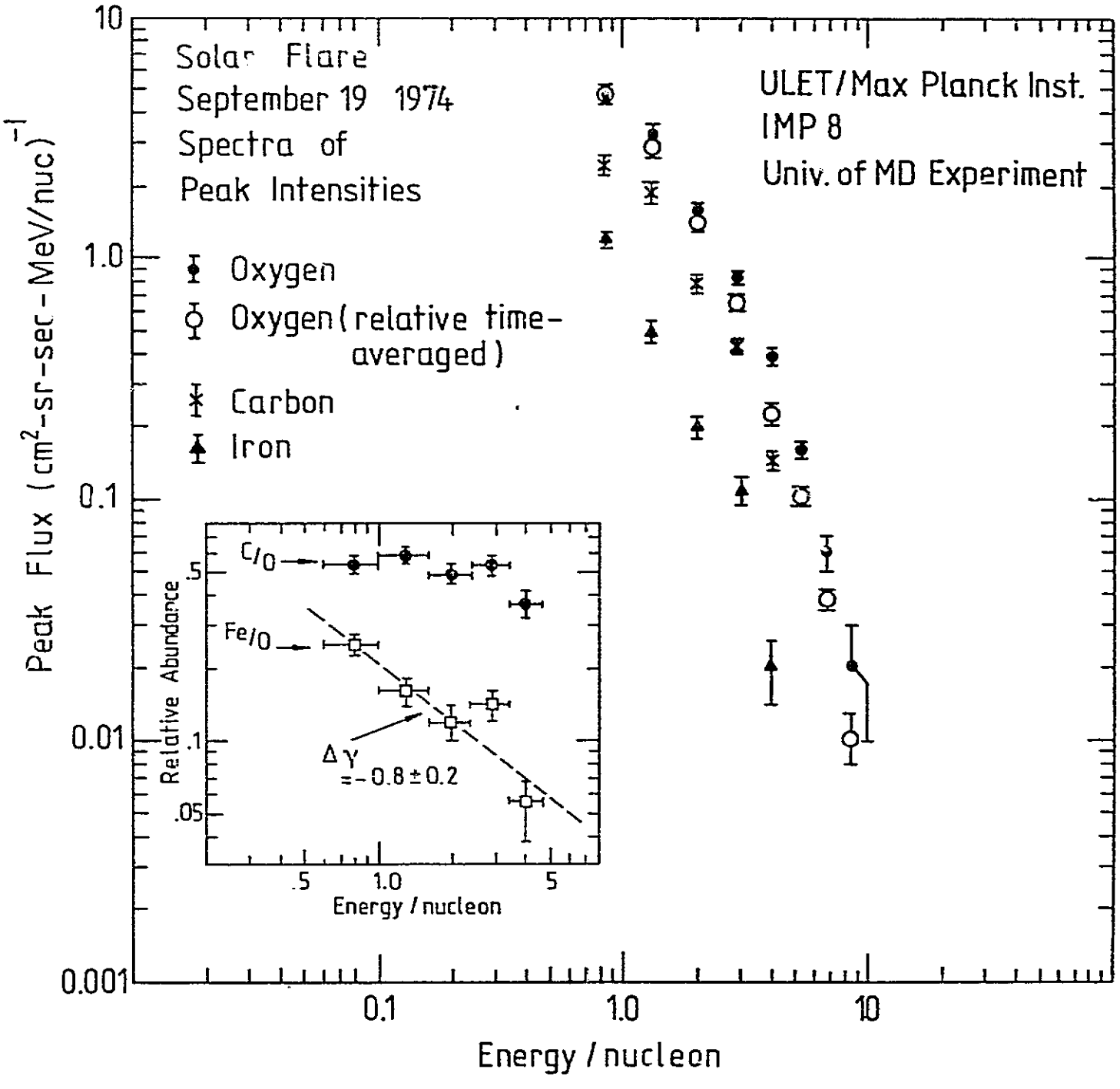
Solar Flare
September 19 1974
Spectra of
Peak Intensities
ULET/Max Planck Inst.
IMP 8
Univ. of MD Experiment
Oxygen
Oxygen (relative time-averaged)
Carbon
Iron
Peak Flux (cm²-sr-sec-MeV/nuc)⁻¹
Energy / nucleon
C/O
Fe/O
Relative Abundance
Δγ
=-0.8±0.2
Energy / nucleon

FIGURE 2

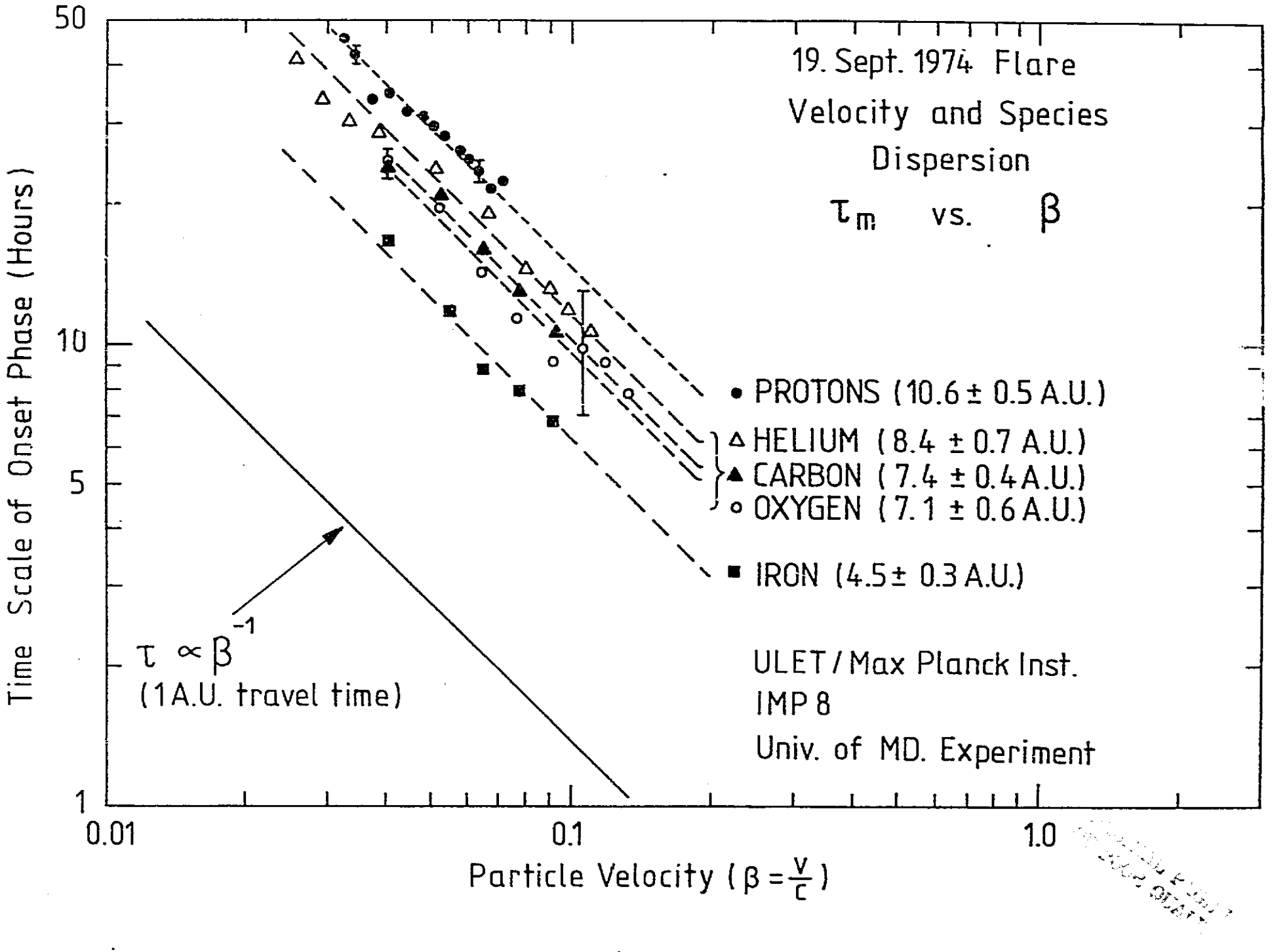
19. Sept. 1974 Flare
Velocity and Species
Dispersion
τ_m vs. β
• PROTONS (10.6 ± 0.5 A.U.)
△ HELIUM (8.4 ± 0.7 A.U.)
▲ CARBON (7.4 ± 0.4 A.U.)
○ OXYGEN (7.1 ± 0.6 A.U.)
■ IRON (4.5 ± 0.3 A.U.)
$\tau \propto \beta^{-1}$
(1 A.U. travel time)
ULET / Max Planck Inst.
IMP 8
Univ. of MD. Experiment
Time Scale of Onset Phase (Hours)
Particle Velocity ($\beta = \frac{v}{c}$)
50
10
5
1
0.01
0.1
1.0

FIGURE 3