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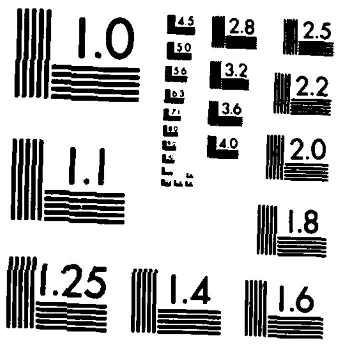

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AD-A143 181

A Determination of the Charge State of Energetic Magnetospheric Ions by the Observation of Drift Echoes

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15 June 1984

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This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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The mean charge states of heavy ions trapped in the earth's magnetosphere are important parameters for distinguishing among magnetospheric theories. No direct measurements have been made at energies greater than ~ 50 keV. A technique that uses the E/q dependence of ion drift velocity is described in this report. To illustrate the application of this technique, a drift-echo

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cont event that followed a substorm occurring at 2100-2200 UT on 25 February 1979 is discussed. In this event the charge state of helium ions was +2 and that of CNO ions was > +2 and probably ≥ +5. This result implies that the drift-echo particles were from freshly injected solar-wind plasma.

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PREFACE

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FIGURES

I. INTRODUCTION

The mean charge states of heavy ions trapped in the earth's magnetosphere, in particular those of the abundant heavy ions He, C, and O, are important observational parameters predicted by various theories of the origin and evolution of the magnetospheric plasma (e.g., Spjeldvik and Fritz, 1978a, b). Up to the present time satellite instrumentation capable of determining the charge state of heavy ions with energies above ~ 50 keV has not been flown. Consequently there is motivation to develop indirect methods of determining the charge state of energetic magnetospheric ions, even if such methods do not have universal applicability. One such method is to measure the drift speed of an ion in the magnetic field of the earth.

The angular velocity Ω_3 associated with the azimuthal drift of an energetic ion is given by the relationship (cf., Schulz and Lanzerotti, 1974)

$$\Omega_3 \propto f(\alpha_o)LE/q \tag{1}$$

where E is the kinetic energy of the ion, q is the charge state, and α_o is the equatorial pitch angle. Here it is assumed that the energy of the ion is sufficiently high that the effect of magnetospheric electric fields on drift is not significant. The important feature to note is that the drift velocity of an ion at a given L value and pitch angle depends upon the ratio of its total energy to the effective charge of the ion. Thus a measurement of the drift speed and the energy of an ion determines the charge state.

It is necessary to tag an ion in some way in order to be able to measure its drift speed. The present experimental procedure uses observations of certain transient enhancements in the ion fluxes which are generated when a group of ions is injected and/or preferentially accelerated at some localized point in the magnetosphere (for example by a substorm in the midnight sector). Ions drift westward around the earth and can be seen at longitudes well away from the injection point (Lanzerotti et al., 1971; Belian et al., 1978). Since the enhancement is localized in longitude, a transient pulse of particles will be seen. Frequently the ions return several times to the location of an observing satellite, hence the term "drift echoes". Because the drift speed of an ion is energy dependent, the pulse of increased flux is seen in different energy channels of a satellite detector at different times.

The drift speed of an ion depends upon the actual configuration of the earth's magnetic field at the time of the observations. Protons are used to determine the relationship between arrival time and energy/charge in the actual magnetic field configuration of the earth at the time of the drift-echo event. Pr^tons can have only one charge state, and no charge ambiguity can result. When the drift rates of the heavier ions are measured at known energies, a comparison of their drift rates with that of protons gives a measure of the ionic charge.

Drift-echo peaks frequently are observed to have a complex shape and do not exhibit a simple rise and fall (Belian et al., 1982). One sees several "peaks" very close together. These "structured peaks" could result from several causes, including an injection multiple in time or longitude; there being more than one relatively abundant charge state of a given ion; multiple ion species being detected in a single sensor; and charge exchange causing the charge state of an individual ion to vary significantly on the drift time scale. Observation of the evolution of a structured peak with longitudinal drift can help to distinguish between some of these possibilities.

II. RESULTS

The results discussed in this report are from data acquired by Los Alamos instruments aboard the synchronous altitude satellites 1976-059 and 1977-007, and from Aerospace instruments aboard the SCATHA (1979-007) near-synchronous satellite. SCATHA is in an orbit with an apogee of $\approx$ 43200 km (R = 7.8 R_E), perigee of $\approx$ 27500 km (R = 5.3 R_E), and an inclination of 7.8°. The Los Alamos sensors of interest covered the proton energy ran from 145 keV to 800 keV (13 channels). The Aerospace sensors covered the er gy range from 54 keV to 717 keV for protons (4 channels), from 396 keV to 9[illegible]V for helium ions (2 channels), and from 1264 keV to 2704 keV for CNO ions (3 channels). The Los Alamos instruments are described in a paper by Baker et al. (1979) and the Aerospace instruments in a paper by Blake and Fennell (1981).

In this report a representative drift-echo event will be examined which was first seen at the location of SCATHA at $\approx$ 21:10 UT on 25 February 1979. At this time the satellites were located as shown in Figure 1. SCATHA was between 1976-059 and 1977-007 in longitude, and was also at L = 6.6. All three satellites were in the post-noon quadrant. This chance configuration is ideally suited for study of a drift-echo event.

Figure 2 presents the proton spectrum as observed at 1976-059 and at SCATHA. No normalization of the data has been done. The spectrum is generated by taking the fluxes observed in each energy channel at the time of the maximum of the first peak in each channel. Thus the spectrum is not the energy spectrum as seen at any instant of time at the observing satellites. It should be the proton energy spectrum at the injection point following

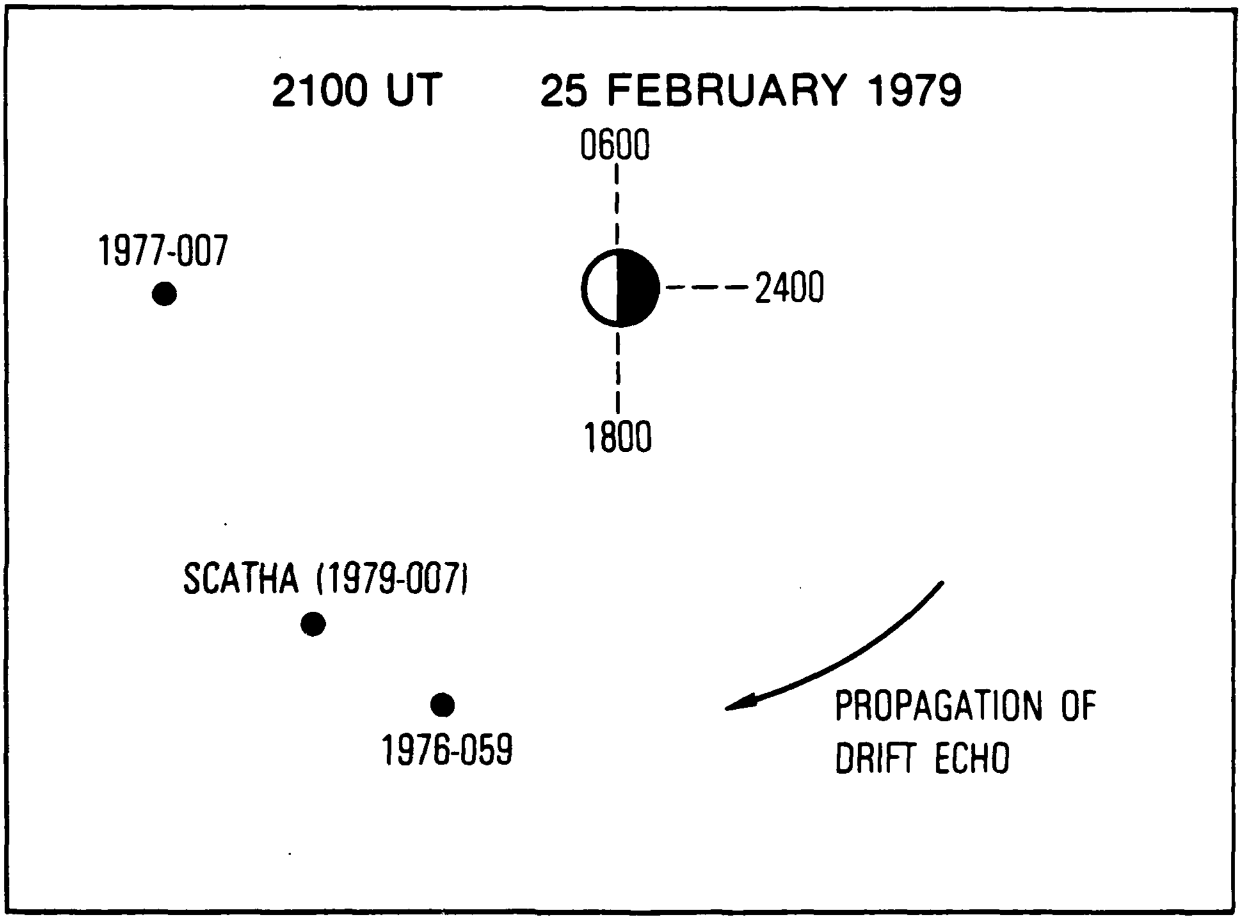

Figure 1. The magnetospheric locations of the three satellites is shown at the time of the onset of the drift-echo event.

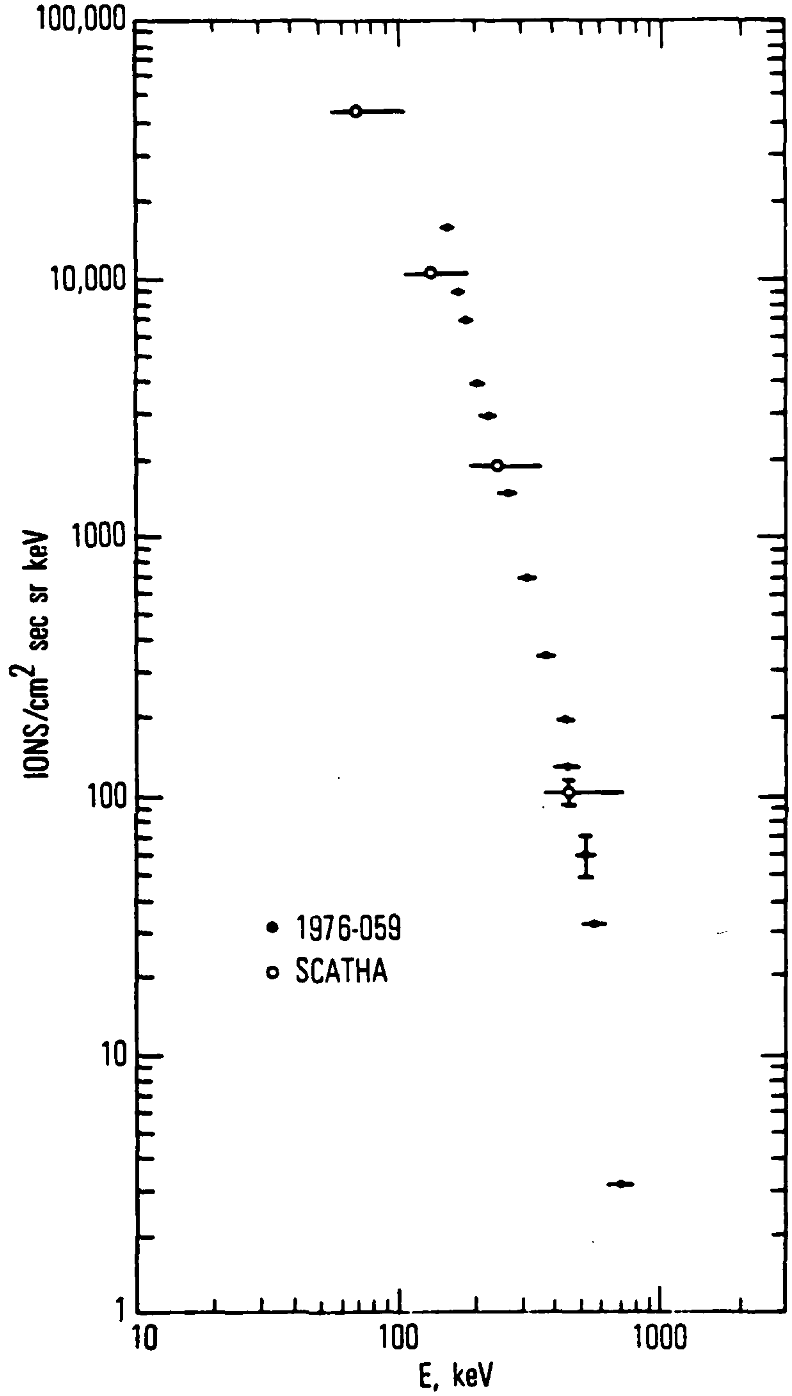

Figure 2. The drift-echo energy spectrum is shown as measured at 1976-059 and SCATHA.

acceleration before drift dispersion begins if strong, energy-dependent loss processes have not distorted the energy spectrum between the injection point and observation locations. The fact that repeated echoes (multiples of 360° of drift) are seen in this event suggests that substantial losses did not occur between the injection point and the first observations of the event, which involved a drift of less than 180°. There is excellent agreement between the two sets of measurements and, furthermore, the data from the third satellite, 1977-007, fall on the same curve (but are not plotted to avoid cluttering the figure). If strong particle losses were occurring a substantial difference in the energy spectra would be expected at the three different longitudinal locations.

A cross-correlation analysis was performed between the data from the 290-340 keV channel and the 400-480 keV channel of both 1976-059 and 1977-007. The expectation was that the peak in the lower-energy channel would lag the peak in the higher-energy channel by a larger time interval at 1977-077 than at 1976-059; 1977-007 is 66° further than 1976-059 from the putative injection region (Belian et al., 1978; Baker et al., 1979) in the midnight sector (cf., Figure 1). The results of this analysis are as follows:

$$\begin{aligned} &\text{1976-059:} \quad \Delta t = 0.85 \pm 0.05 \text{ minutes} \\ &\text{1977-007:} \quad \Delta t = 2.05 \pm 0.05 \text{ minutes} \end{aligned} \tag{2}$$

A relative shift of significantly more than ± 0.05 minutes from the given Δt rapidly reduces the correlation between two energy channels, and thus is a measure of the uncertainty in the derived value of Δt. These observations lead to a measure of the separation rate per degree of longitude:

$$(\Delta\Omega)^{-1} = (1.82 \pm 0.15) \times 10^{-2} \text{ minutes/deg} \tag{3}$$

A dipolar calculation (Schulz and Lanzerotti, 1974) of the expected drift speeds of 290 keV and 400 keV protons yields

$$\begin{aligned} 1/\Omega(290) &= 6.36 \times 10^{-2} \text{ minutes/deg} \\ 1/\Omega(400) &= 4.61 \times 10^{-2} \text{ minutes/deg} \end{aligned} \tag{4}$$

or

$$(\Delta\Omega)^{-1} = 1.75 \times 10^{-2} \text{ minutes/deg} \tag{5}$$

This value is in excellent agreement with the observations, cf., (3), and indicates that the dipole approximation is a good one for ordering the observations in this event.

The count rates as a function of time for selected ion channels of SCATHA are shown in Figure 3. These data are for pitch angles of 90° ± 30°. The drift speed of an ion is a function of pitch angle; however, a dipolar calculation predicts only a 5% difference between the extremes of 60° and 90°. The dispersion in arrival time as a function of ion energy can be seen clearly in Figure 3 although, because of the averaging of the data that was done to generate the figure, it cannot be used for quantitative timing purposes. Note that the peak in the 363–717 keV proton channel occurs prior to either of the helium peaks. There was only one CNO count in the five hours preceding the event, and it was in the lowest-energy channel; these CNO counts can be associated with the drift-echo event with confidence.

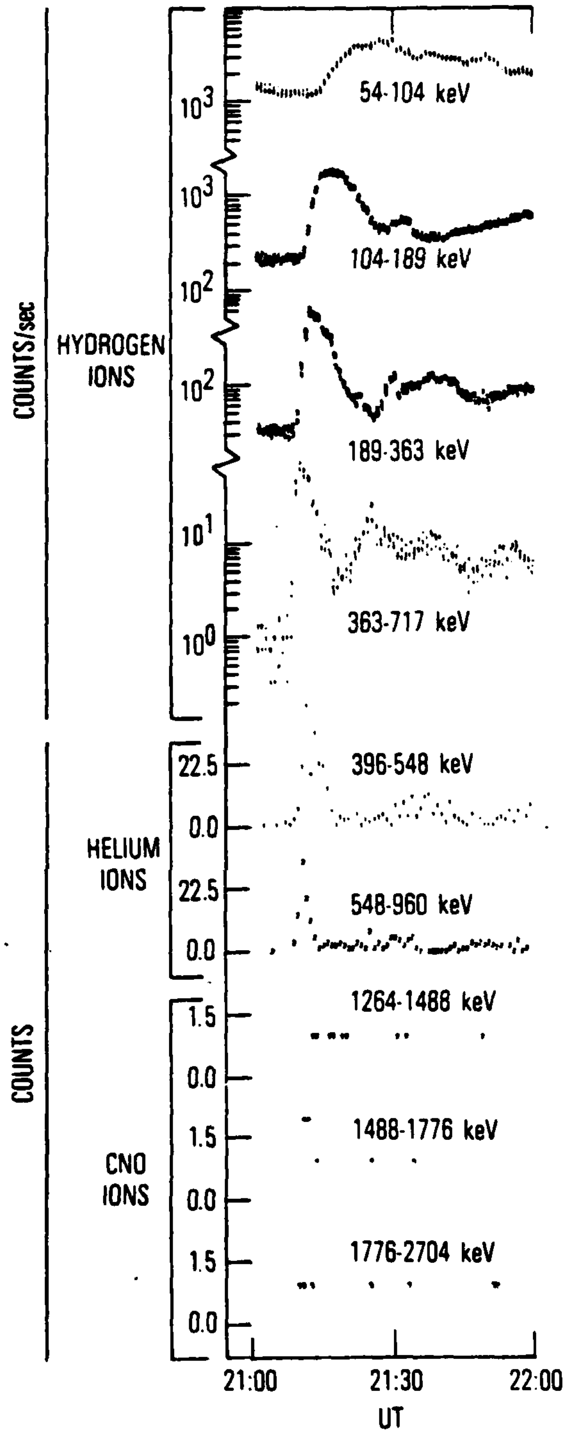

Figure 3. The temporal history at the onset of the drift-echo event of the count rates in nine channels is shown as observed at SCATHA.

In order to make a quantitative estimate of the E/q values for the 396-548 keV and 548-960 keV helium channels, a cross-correlation analysis was performed between these two channels and the 104-189 keV, 189-363 keV, and 363-717 keV proton channels. The results are shown in Figure 4, where the time differences between the arrival of helium ions (in both energy channels) and the arrival of protons (in three energy channels) are plotted against the reciprocal of the energy of the proton channel in question. The vertical bars indicate the timing uncertainty. A straight line is expected; the intersection of a straight-line fit with zero time difference gives the E/q of the helium ions. The results are 190 keV/q and 270 keV/q.

These calculated values may be compared with the actual channel thresholds. For $q = 1$, E/q amounts to 396 keV/q and 548 keV/q, and for $q = 2$, E/q amounts to 198 keV/q and 274 keV/q, respectively. The straight-line fits gave values of E/q only 8 keV and 4 keV different from the known values for $q = 2$. Clearly the helium ions observed in this drift-echo event were stripped.

An upper limit to the fraction of singly charged ions can be derived by assuming all the counts around the expected time of arrival of He^+, prior to the arrival of He^{++}, are due to singly charged helium. The fraction is

$$He^+/He^{++} < 0.03 \tag{6}$$

A low helium ion count rate was seen for a few hours prior to the drift-echo event, indicating a pre-existing flux. The count rate at the expected time of the He^+ drift echo is no greater than the pre-existing flux, and thus the observations are consistent with there being no He^+ ions in the drift-echo event.

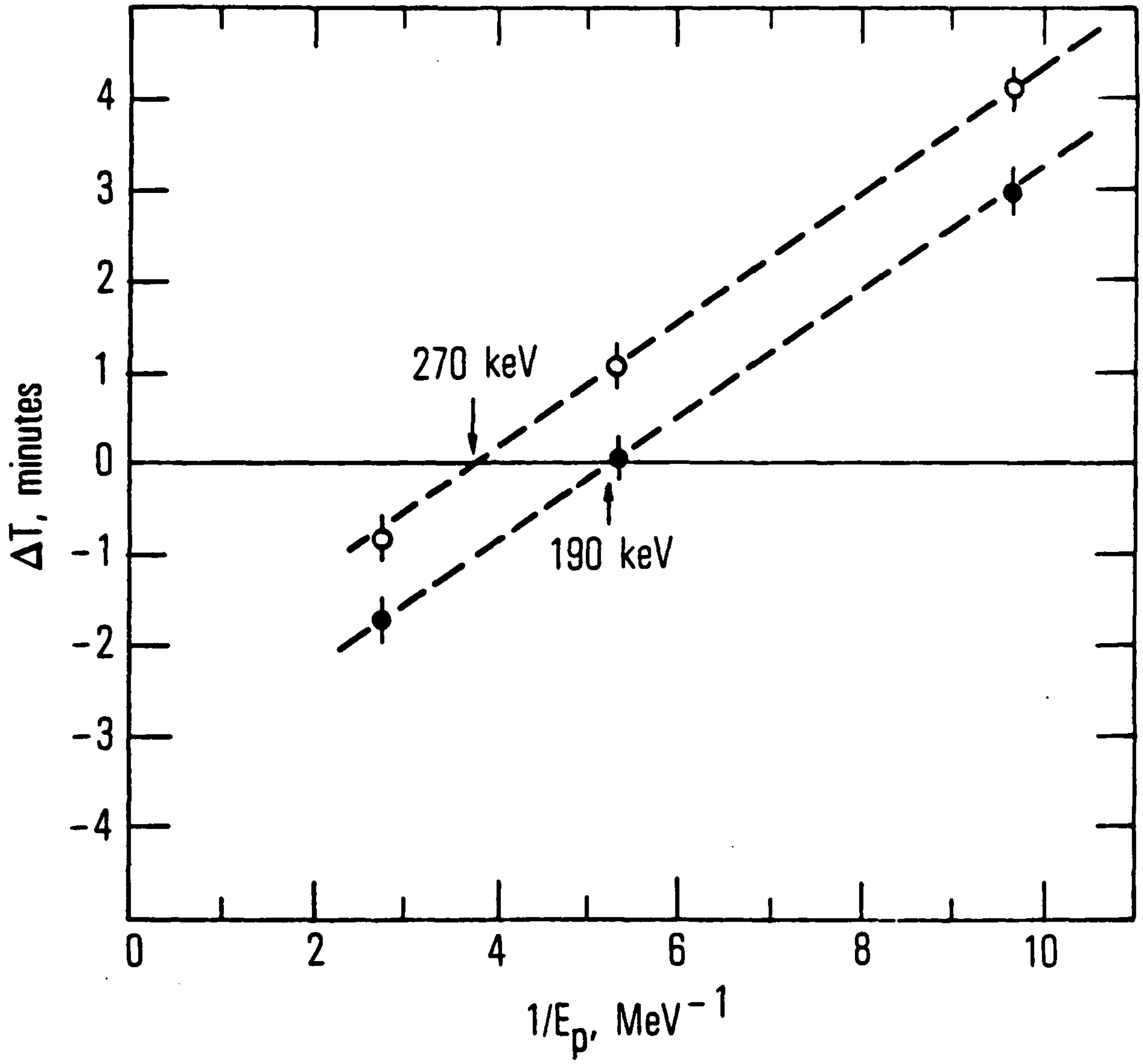

Figure 4. A plot of the time delay between the two helium channels and three proton channels is plotted versus the reciprocal of the proton energy. The open points are the proton correlations with the 548-960 keV helium channel; the solid points are the proton correlations with the 396-548 keV helium channel.

A similar cross-correlation analysis is not practical for the CNO channels because of the paucity of counts, cf., Figure 3. Although a quantitative analysis would be difficult, several features of the data are noteworthy:

1. The first CNO count does not appear until ~ 0.5 minutes after the increase in count rate in the 396-548 keV helium channel. Since it was shown that $q = 2$ for helium, the largest value of E/q in the 396-548 keV passband is $548/2 = 274$ keV/charge. This result implies E/q for the CNO ions is less than 274 keV/charge.

2. The three CNO energy channels show the expected energy dispersion; the counts appear in order of decreasing energy.

3. The CNO "peak" is broader than would be expected if q equaled 1 or 2.

4. The CNO peak is located ~ 3 minutes later than the predicted position for $q=1$ as derived from the proton observations.

5. There are a total of 14 counts in the CNO "peak" (summed in all three channels). In order to improve the statistics the CNO counts have been examined at all pitch angles, and not just in the 60-120° antisolar pitch-angle bin which is plotted in Figure 3. There are 60 additional counts for a total of 74. Not one appears prior to the onset indicated in Figure 3.

These observations are consistent with the CNO charge state being 5 or more. The probability that the charge state was 1 or 2 and that the observed timing was a result of statistics is nil. For charge state 3 and especially charge state 4 the observed timing possibly could be a result of statistical fluctuations. The probability would be difficult to assess and likely would require a numerical simulation.

III. DISCUSSION

The results of this study show that the helium ions were stripped, and that the CNO ions were probably of charge state 5 or higher, and definitely not charge state 1 or 2. These results indicate that the source of the energetic ions was not the ionosphere. Furthermore these ions could not have been resident in the synchronous altitude region for a long time before acceleration. If they had been, then charge exchange would have transformed the stripped, or nearly stripped, solar-wind ions (Spjeldvik and Fritz, 1978a; 1978b) to a lower charge state than is observed. A model in which plasma sheet ions, originally from the solar wind, are brought in from the tail and accelerated would fit the observations (Baker et al., 1982).

Fritz and Wilken (1976) have shown that the energetic heavy-ion fluxes in the synchronous altitude region are highly time variable and that, above a few hundred keV, CNO ions are the most abundant. Their results, and the present ones, suggest that the most-energetic ions in the synchronous altitude region result from injections of plasma sheet ions accelerated by electric fields. If the plasma had a steep energy spectrum prior to acceleration, the several-fold increase in the CNO energy relative to that of protons, because of their high charge state, could make them most abundant in the energized plasma population.

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