CHARACTERISTICS OF THE SPECTRA OF PROTONS AND ALPHA PARTICLES IN RECURRENT EVENTS AT 1 AU

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Abstract. The spectra of both protons and alpha particles ($1 \lesssim E \lesssim 7$ MeV/nucleon) during 31 recurrent particle streams are fit well by an exponential in particle rigidity. Although the spectra show considerable temporal variation, the proton and alpha particle spectra are correlated such that the e-folding rigidities $P_o(\alpha)$ and $P_o(p)$ of the two spectra are in the ratio $P_o(\alpha)/P_o(p) = 1.5 \pm 0.1$. The consistency of this ratio may be a characteristic of the interplanetary acceleration process.

Introduction

A number of recent observations of low energy cosmic rays have provoked renewed interest in recurrent energetic particle events, often called "corotating" events because they recur with successive solar rotations at ~ 27 day intervals. Until recently, recurrent events had generally been assumed to be of solar origin. However, observations from Pioneer 10 and 11 have provided evidence that particles are accelerated in the interplanetary medium beyond ~ 2 AU [McDonald et al., 1976; Barnes and Simpson, 1976; Pesses et al., 1978]. In this letter, we report a comprehensive study of the differential energy spectra of H and He nuclei with ≥ 1.4 MeV/nucleon in recurrent events at 1 AU, and examine the implications of the characteristics of these spectra for the particle source and the acceleration mechanism. A preliminary report of this work has been given by Mewaldt et al. [1978].

Observations

This study includes 31 individual recurrent events from three long-lived corotating particle streams. Stream #1 (11/73 to 8/74) and Stream #2 (12/73 to 9/74) existed simultaneously in the interplanetary medium with a phase difference of ~ 150° in solar longitude. Our observations of Stream #3 extend from 10/75 to 7/76. Intensity-time plots of ~ 1 MeV protons in these same streams can be found in McDonald et al. [1976] and Van Hollebeke et al. [1978]. Two recurrent events within these periods were not considered in this study because of contamination by solar flare particles.

Our observations were made at 1 AU with the Caltech Electron/Isotope Spectrometers on IMP-7 and 8 [Mewaldt et al., 1976]. From 1.4 to 2.3 MeV/nucleon H and He are identified by their energy loss in a ~ 50 μm thick silicon solid-state detector (D2) while H and He with ≥ 2.5 MeV/nucleon are identified by standard techniques based on energy loss ΔE in D2 and the residual energy loss E' in a 1 mm detector (D5).

We find the differential energy spectra of both H and He observed in these 31 events to be incompatible with a power law in kinetic energy/nucleon over anything but a limited energy range, in contrast to typical solar flare energy spectra observed at $\lesssim$ 10 MeV/nucleon. On the other hand, exponential rigidity spectra of the form

$$\frac{dJ}{dP} \propto \exp(-P/P_o) \qquad (1)$$

provide good fits to our observations, as has also been reported by McDonald et al. [1976] and Van Hollebeke et al. [1979]. Figure 1 shows examples of our spectra from recurrent events along with least squares fits, where we note the excellent agreement with (1). Spectra from twenty time periods have been analyzed with the detailed energy resolution shown in Figure 1. Much of the following analysis is based on data accumulated from both instruments within four matched energy intervals from 1.4 to 12.5 MeV/nucleon. Fits with these energy intervals did not differ significantly from the corresponding fits to the more detailed spectra such as in Figure 1. In order to ensure adequate event statistics for both H and He, a common energy interval of 1.4 to 7.0 MeV/nucleon was used to fit daily average spectra using (1) for all days within the 31 recurrent events. This interval corresponds to rigidities of 52 to 116 MV for protons and 104 to 232 MV for ^{4}He.

In Figure 2 we show the time history of the 1.4 - 2.3 MeV proton flux for two time periods, along with the results of fits to equation 1. The second time period (74:216-237) consists of two recurrent events associated with separate high speed solar wind streams. The middle panel of Figure 2 shows the e-folding rigidities, where we note that while there is considerable variability in the spectra, the H and He variations are correlated, with the He spectra always harder than the H spectra. As in Van Hollebeke et al. [1979], we find that the spectra typically harden during the event, as seen during days 74:177-182 and 74:231-237. The top panel of Figure 2 shows the ratio of the e-folding rigidities determined for H and He. Note that in spite of spectral variations, the ratio $P_o(\alpha)/P_o(p)$ is always ~ 1.5.

A comprehensive comparison of the e-folding rigidities is shown in Figure 3, which includes the 90 days for which the ratio $P_o(\alpha)/P_o(p)$ could be determined to a statistical accuracy of ≤ 10%. A histogram of this ratio is also shown. Note that although both the proton and alpha e-folding rigidities vary by a factor of ~ 3, their ratio is constant to within a few percent, with $P_o(\alpha)/P_o(p) = 1.5 \pm 0.1$ characteristic of these time periods. We observe some events with a proton P_o as low as ~ 6 MV. For such soft spectra, too few He nuclei are observed to determine accurately the He spectrum over one day. However, several

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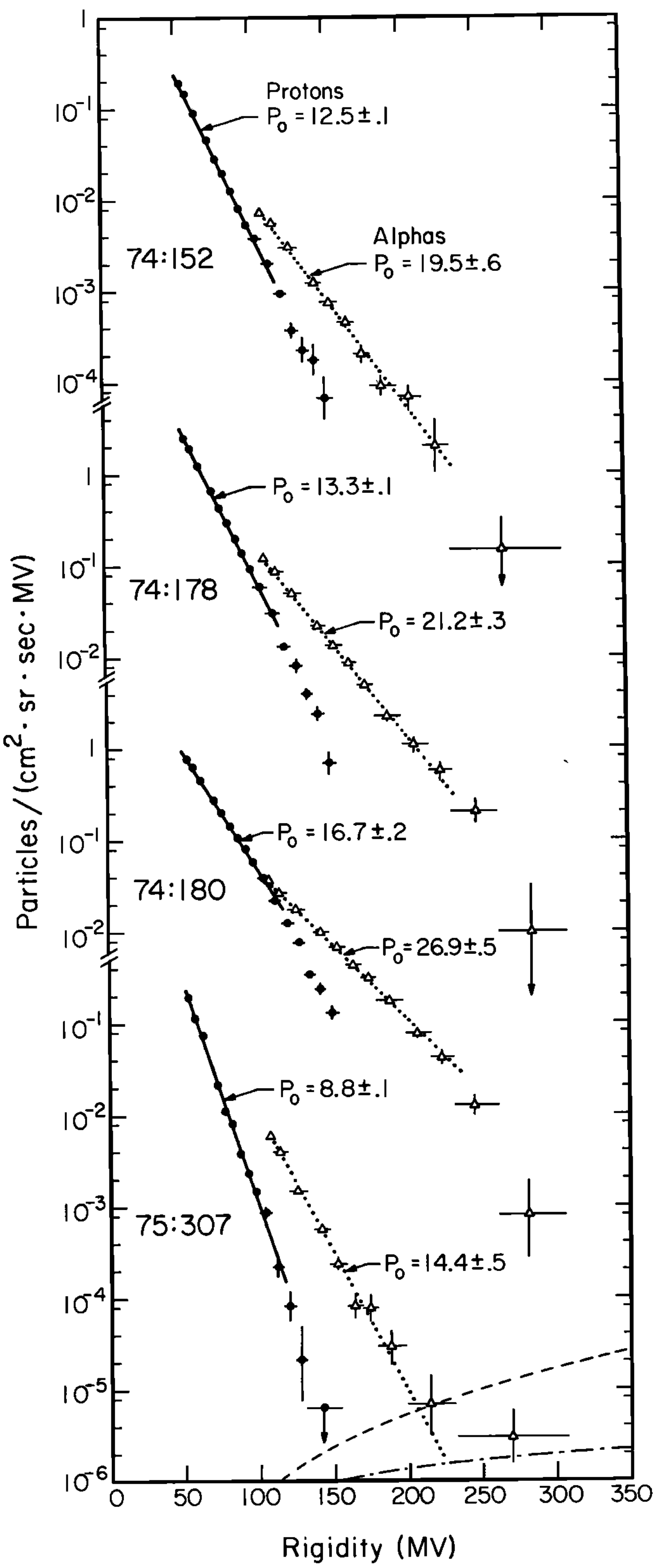

Fig. 1. Examples of rigidity spectra for protons and alpha particles from several recurrent events. Fits to an exponential rigidity spectrum are shown over the rigidity intervals used in the comparison of the spectra. The resulting e-folding rigidities (P_0) and typical quiet time flux levels for protons (dashed line) and alpha particles (dot-dash line) are also indicated.

day averages of these soft spectra also give $P_0(\alpha)/P_0(p) = 1.5 \pm 0.1$.

For about one-third of the daily proton spectra, the intensity at rigidities $\gtrsim$ 120 MV falls significantly below an extrapolation of the fit to (1) at lower rigidities (see e.g., day 74:180 in Figure 1). The vast majority of these deviations from exponential behavior occur after the time of maximum intensity of the event. This "softening" of the spectra may represent a decrease in the acceleration efficiency at high rigidities, or it might suggest that a slightly different spectral shape is more appropriate to this wider rigidity interval. We have considered spectra of the form

$$\frac{dJ}{dP} \propto P^n \exp(-P/P_0) \qquad (2)$$

with n an integer, which are very similar in shape to (1). From a chi-square analysis of the twenty spectra analyzed in detail, we find that the case n = 0 (equivalent to equation 1) provides the best fit to the ensemble of the spectra. However, individual spectra are in some cases clearly better fit by values of $n \neq 0$. In ~ 75% of the cases the best-fit value of n is in the range $-2 \leq n \leq 2$. Note that with, for example, $n > 0$ somewhat smaller values of P_0 result. However, we find that the relation $P_0(\alpha)/P_0(p) \approx 1.5$ is still maintained for $n \neq 0$.

Implications of the H and He Spectra

The characteristic $P_0(\alpha)/P_0(p) \approx 1.5$, which is surprisingly well preserved from event to event and throughout the evolution of individual events, could result from the acceleration mechanism, from subsequent interplanetary propagation, or from some combination of these. For example, it is possible that the temporal variations in the spectra (typically hardening during the event as in Figure 2) could result from the increasing distance between the source and observer, combined with a rigidity-dependent radial gradient. It is not apparent, however, that rigidity-dependent propagation can maintain both the exponential nature of the spectra and the relation $P_0(\alpha)/P_0(p) \simeq 1.5$ as the distance from the source varies.

Although a more detailed study of the effect of interplanetary propagation on the spectra of recurrent events is needed, the consistent signature demonstrated in Figure 3 suggests that these observed features may be characteristic of the acceleration mechanism, largely unaltered by interplanetary propagation. In this case the observed spectral variations with time (Figure 2) would be due to changes in the source spectra. This interpretation is supported by simultaneous observations beyond ~ 2 AU and at and within 1 AU, which show nearly identical proton spectral slopes at different radii [Van Hollebeke et al., 1979] and also show no radial dependence in the He/H ratio at 0.6-1.8 MeV/nucleon [Christon and Simpson, 1979].

Previous studies have generally considered the relative He and H abundances in terms of equal energy/nucleon. On this basis, our He/H ratio varies by a factor of ~ 3 over these 31 events, with a mean of 0.057 at 1.4-2.3 MeV/nucleon, consistent with other studies [Zwickl et al., 1978; McGuire et al., 1978; Christon and Simpson, 1979] at similar energy/nucleon. Our mean value is somewhat greater than the mean of 0.033 obtained by Marshall and Stone [1978] for an earlier and more heterogeneous data sample, but it is consistent with their observation that He/H is on average greater during high speed solar wind streams. In the 2.5-4.0 MeV/nucleon interval we find an event mean of He/H = 0.038, while at 0.6-1.0 MeV/nucleon Scholer et al. [1979] find He/H = 0.07-0.10, and thus the He spectra are softer than the H spectra on an energy/nulceon basis, as was found also by Marshall and Stone [1978]. Based on the similarity of the He/H ratio in the 1.5-8.8 MeV/nucleon interval to that in the solar wind, McGuire et al. [1978] suggested that the acceleration was rigidity independent. Apparently this similarity is accidental, since the H and He spectra are not identical on either an energy/nucleon or rigidity basis.

If compared in the same rigidity interval, we find that He/H is typically $\gtrsim$ 1 at rigidities > 100 MV, again with considerable variation from event to event (see, e.g., Figure 1). We find that the apparent compositional variations from event to event are in general correlated with spectral slope, with the periods having larger values of P_0 giving larger He/H ratios on an equal energy/nucleon basis. From this and the above considerations, we conclude that is is necessary to take into account the H and He spectral differences to gain a meaningful measure of the He/H abundance ratio.

One possible approach to considering spectral differences is to integrate the spectra, thereby obtaining the ratio of the integrated fluxes, a procedure that necessitates extrapolating the observed spectra to zero rigidity. Following

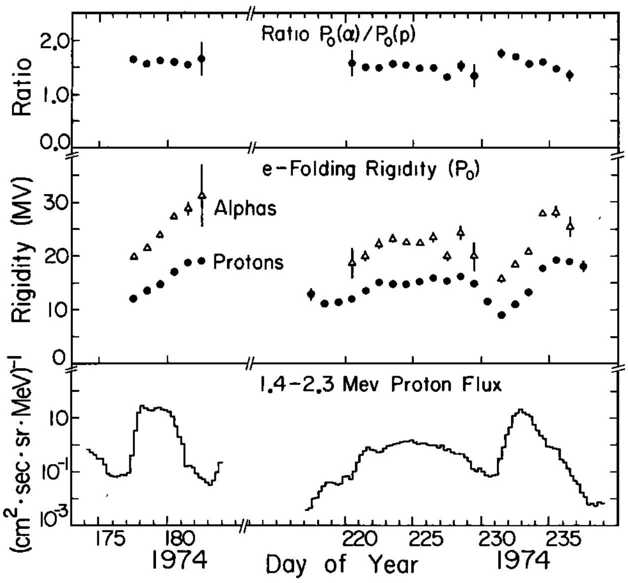

Fig. 2. Typical recurrent events. Plotted are the 1.4-2.3 MeV proton flux, the daily average e-folding rigidities for protons and alpha particles, and the resulting ratio $P_0(\alpha)/P_0(p)$. Statistical uncertainties ($\pm 1\sigma$) are shown when they exceed the size of the data points.

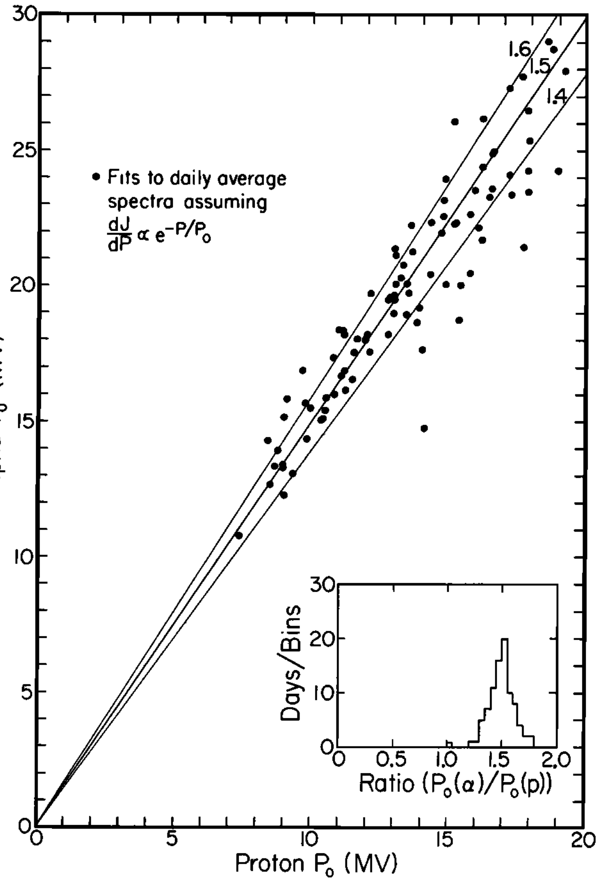

Fig. 3. Comparison of daily average e-folding rigidities for protons and alpha particles. The inset shows a histogram of the ratio $P_0(\alpha)/P_0(p)$.

this approach, we find that the ratio of the integrated fluxes is typically He/H = 0.2 ± .08 This value is somewhat greater than is characteristic of typical source populations of lower energy particles. Clearly, additional measurements are required to determine whether the exponential character of the spectra is in fact maintained down to low rigidities. If so, an integrated flux ratio of He/H = 0.2 might suggest that either the source composition of the recurrent fluxes is relatively helium rich, or that the acceleration mechanism has preferentially selected He over H, possibly on the basis of its charge to mass ratio.

Discussion

There have been several suggested mechanisms to account for the evidence of particle acceleration in interplanetary space. McDonald et al. [1976] considered second order Fermi acceleration by Alfvén discontinuities at stream-stream interaction regions. Although Fermi acceleration can produce exponential rigidity spectra at nonrelativistic energies and may in some circumstances favor ^4He over ^1H [see, e.g., Sakurai, 1974 and references therein], it would not produce the spectral ratio $P_0(\alpha)/P_0(p) \sim 1.5$ without additional assumptions.

In Jokipii's treatment of Fermi acceleration [Jokipii, 1966], spectra of the form $dJ/dT \propto T\exp(-V/V_0)$ are obtained, where T is kinetic energy, and V is velocity. At nonrelativistic energies this spectral form is equivalent to $dJ/dP \propto P^3 \exp(-P/P_o)$, i.e., n = 3 in equation 2. Although similar in shape, this spectral form fit better than equation 1 for only 3 of the 20 proton spectra considered in detail. In addition, this model would not predict $P_o(\alpha) \simeq 1.5\ P_o(p)$ [J. R. Jokipii, private communication, 1979].

Another suggested acceleration mechanism is transit time damping [Fisk, 1976], which predicts spectra of the form $dJ/dT \propto T \exp(-T/T_o)$. Fits of this function, or of $dJ/dT \propto \exp(-T/T_o)$ are possible over only a limited energy range.

Pioneer 10 and 11 observations have shown a direct association of recurrent events beyond ~ 2.5 AU with corotating interaction regions (CIR's) caused by the interaction of adjacent fast and slow solar wind streams. Barnes and Simpson [1976] and Pesses et al. [1978] have presented evidence for acceleration of protons > 0.5 MeV by forward and reverse shock pairs that form at CIR boundaries. For reverse shock events Barnes and Simpson find typical He/H ratios of .05 to .10, consistent with an extrapolation of the 1 AU spectra to lower energy. In addition, the spectra of reverse shock events harden with time, as we observe in most 1 AU events. If the 1 AU events represent the upstream flow of particles accelerated by shocks beyond ~ 2 AU, these comparisons suggest that reverse shock particles dominate 1 AU events. This suggestion is strengthened by the observation that the onset of 1 AU events usually coincides with a high speed solar wind stream [Van Hollebeke et al., 1979], as expected for particles upstream from the reverse shock [see, e.g., Palmer and Gosling, 1978].

Post-submission Note. After submitting this paper, we received a preprint from Gloeckler et al. [1979] which also presents H and He recurrent event spectra. They find the spectra of H and He to be well represented by a function which is equivalent to using n = 3 in equation 2. In our notation, they find $P_o(\alpha) \simeq 2\ P_o(p)$, while we find $P_o(\alpha) \approx 1.6\ P_o(p)$ for n = 3. However, as pointed out by Gloeckler et al. [1979], there is an apparent experimental discrepancy in the sense that the P_o values for He measured by the Caltech and Goddard groups are systematically ~ 10 to ~ 40% less than the values obtained by Gloeckler et al. for the same events.

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