IDENTIFICATION OF A HIGHLY VARIABLE COMPONENT IN LOW-ENERGY COSMIC RAYS AT 1 A.U.*

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Evidence is given for the existence of two distinct populations of cosmic-ray protons and alpha particles in the energy range of 4 to 80 MeV/nucleon: (1) a highly variable component with an inverse energy dependence and (2) a quasisteady "residual" component which shows a positive dependency on energy. The analysis is based on a series of four-day energy spectra obtained from the cosmic-ray experiments aboard IMP-IV during the time interval from 24 May 1967 to 20 August 1968. It is suggested that the highly variable component is probably entirely of solar origin. The "residual" component is most likely of galactic origin although below 10 MeV it may also contain some solar particles.

In the past eight years several several studies of low-energy particle populations in space in the vicinity of the earth have been made.[1-4] The resultant proton and alpha-particle energy spectra so determined have exhibited a persistent relative minimum at around 20 MeV/nucleon. There has been considerable disagreement concerning the origin of the particles represented by the turnup in the spectrum on the low-energy side of the relative minimum. It has generally been assumed that particles of galactic origin predominated in the region of the turnup with perhaps an unknown amount of solar particles being present on occasion. Until recently, because of the poor counting statistics for most pertinent experiments in the energy range of interest, it was not possible to see time-dependent spectral features with periods shorter than a few weeks.

This present Letter reports on the analysis of a series of proton and alpha-particle energy spectra having the very good time resolution of several days, as compared to averaging periods of from weeks to months required for previous studies. The results of this analysis show that low-energy cosmic rays in the energy interval of interest appear to be composed of two distinct populations of particles on the basis of their time behavior. These two components are characterized by a large amount of variability in one case and relative constancy in the other, on time scales of the order of months. The highly variable component which is associated with the low-energy turnup mentioned above has a steep monotonically decreasing character. The relatively steady component has a very shallow positive slope. Because of the very close correlation of the variable component with solar activity during solar active periods, one is led to associate this component with an origin at the sun. The second component, or "residual" spectrum, can be considered to represent the modulated galactic component, but may also contain solar particles.

Very good statistics obtained for averaging periods of the order of a few days for the Goddard Space Flight Center cosmic-ray experiments aboard IMP-IV have permitted a degree of time resolution not possible in the previously reported work. These experiments consisted of (1) a silicon solid-state ΔE vs $E-\Delta E$ particle telescope with geometry factor $\simeq 0.6$ cm^2 sr covering the kinetic energy interval of 4 to 19 MeV/nucleon for $Z \leq 2$, and (2) a CsI ΔE vs $E-\Delta E$ telescope with geometry factor $\simeq 3$ cm^2 sr, energy interval 18 to 81 MeV/nucleon, and charge $Z \leq 2$. IMP-IV was launched into an equatorially inclined orbit of 67° on 24 May 1967 with initial perigee of 248 km, apogee of 211 116 km, and period of 104 h.

The proton and alpha-particle spectra obtained for 96-h averaging intervals show great variability in the location of the relative minimum. Four representative sets of spectra taken from the analysis period from 24 May 1967 to 20 August 1968 are shown in Fig. 1. These spectra, which are arranged in order of decreasing total flux, show the relative minimum occurring at correspondingly lower energies. No selection of "quiet" data was utilized in producing the 113 resultant spectra for the 15-month period for which the data were analyzed. Rather, in order to emphasize the role played by solar particles, data representative of large solar-flare-associated particle events were included as well as data from the quietest periods of solar activity. These two extremes are illustrated in Figs. 1(a) and 1(d), the former of which shows the usual monotonically decreasing behavior and high flux level

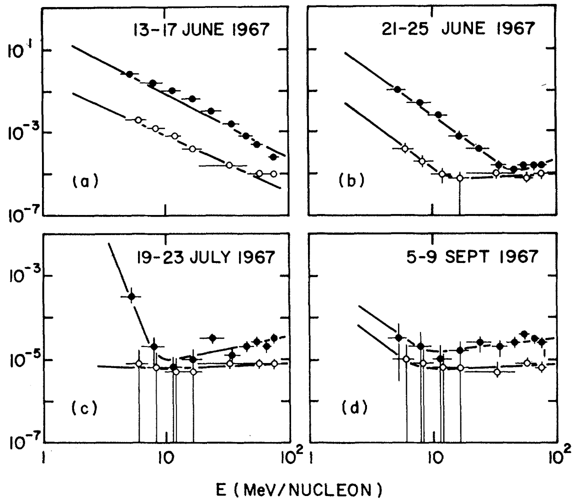

FIG. 1. IMP-IV proton (solid circles) and alpha-particle (open circles) 96-h differential energy spectra.

following a solar flare, and the latter a very low total counting rate associated with a period of minimum solar activity.

This observed behavior of both proton and alpha-particle energy spectra suggests that in the range specified the cosmic rays may be taken as consisting of two components, one originating at the sun and the other being the solar-modulated galactic primaries. It has been shown[5] that over the entire range of observed fluxes for solar-flare-associated particles, the resultant spectra are very well fitted by an exponential in particle rigidity. Over a limited energy range, however, a power law in kinetic energy gives a good fit. On either side of the minimum in the spectra shown in Fig. 1 a power law is seen to give a good fit to the data. Without attaching any special physical significance to such a fit in the limited energy range under consideration, it seems reasonable to attempt to describe the observed fluxes as the sum of two power laws in kinetic energy. The differential flux then may be expressed in the form

$$J(E) = F_S E^{-S} + F_G E^{G}, \qquad (1)$$

in which the first term represents the solar contribution and the second the galactic component. By use of a weighted least-squares fit, the four parameters in Eq. (1) were determined for each of the 96-h spectra obtained. Such fitted spectra are represented in Fig. 1 by the solid curves.

It would seem reasonable to assume that if this model is a good representation of reality then the lower energy, or solar, component would be a more rapidly varying function of time with greater changes than the galactic, or higher energy, component. With this assumption and a form for the spectrum given by Eq. (1) the following behavior would be expected for the particle spectra observed in the energy interval under discussion: (1) independence of the lowest and highest energy fluxes for all cases except the occurrence of a purely solar spectrum, (2) direct dependence of the lowest energy flux upon the energy at minimum flux, (3) independence of the highest energy flux with respect to the energy at minimum flux, and (4) the same power-law index for the minimum flux as a function of the energy at minimum flux as for the galactic component.

The collective analysis of all the 96-h spectra over the 15 months involved showed just the behavior expected. In Fig. 2 are shown the pertinent results for protons. The alpha-particle results were similar in all respects. The independence of the low- and high-energy fluxes is illustrated in Fig. 2(a). Above a flux at 5.2 MeV of about 0.1 proton/sec cm^2 sr MeV the dependency resulting from a pure solar spectrum becomes apparent. Figures 2(b) and 2(c), respectively, show the dependence and independence of the low- and high-energy fluxes with respect to the energy at minimum flux. Finally, Fig. 2(d) may be compared with the proton spectrum in Fig. 1(d), for instance, to see that indeed the two curves are parallel.

Qualitative examination of the helium-to-proton ratios for each set of spectra has shown that the ratios at the lower energies exhibit larger variations with respect to time than do those at higher energies. This observation is consistent with the assumption that the lower energy flux increases are of solar origin. The alpha-particle-to-proton ratio in solar flares has been shown[5] to vary between 10^{-3} and 10^{-1}. At higher energies where the particles are known to be of other than solar origin[6] the ratio approaches a constant value of about 10^{-1}.

Concurrent observations of the sun show that during the period of the analysis under consideration there were a number of recurring calcium plage regions on the solar surface which could be correlated with 27-day-period particle-flux increases. These were in addition to a number of reasonably large solar flares which correspond to large proton events. Although not a proof of the solar origin of all of the lowest energy fluxes observed, these observations of solar related features, it would seem, support the conjecture that the sun is a highly variable source of ener-

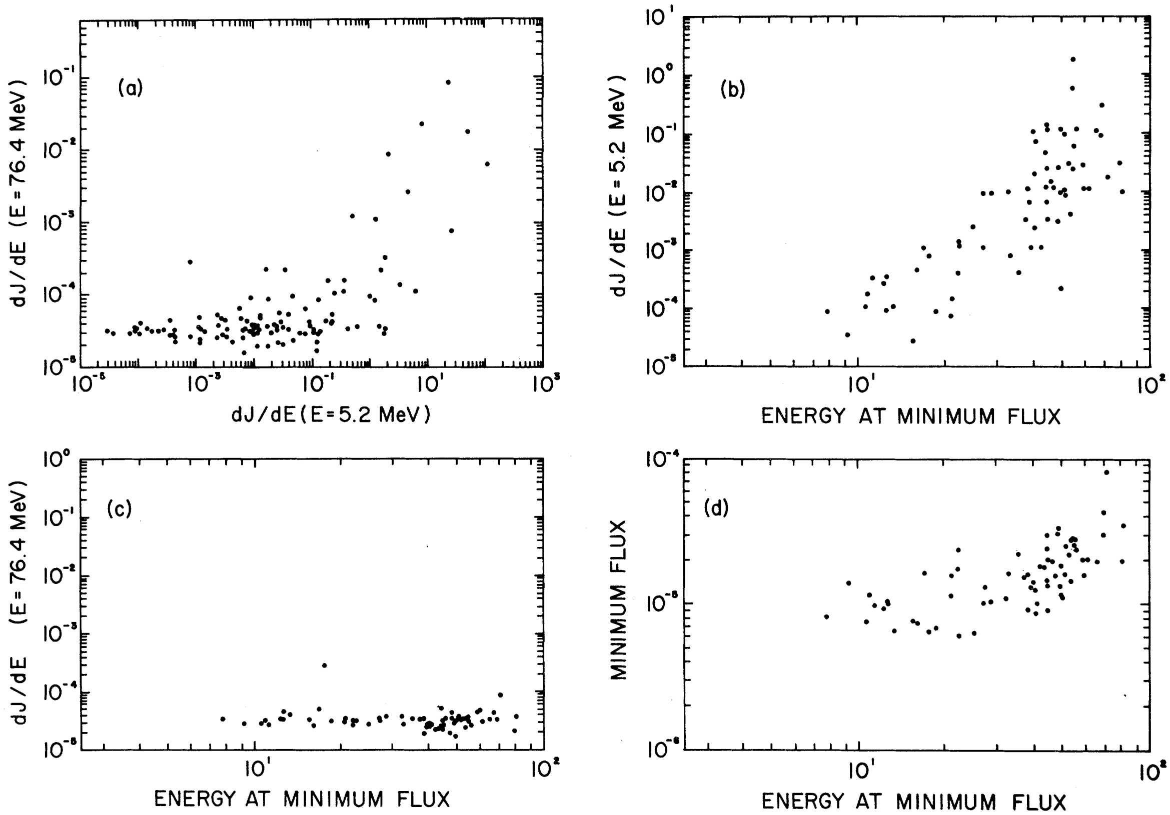

FIG. 2. IMP-IV proton-flux correlation results for 96-h averages covering the period from 24 May 1967 to 20 August 1968. Flux units are number/sec cm^2 sr MeV. Kinetic energy units are MeV.

getic particles at kinetic energies of 20 MeV/nucleon and below.

The two-component model presented here can be interpreted as showing that down to the lower energy bound there was present at all times the highly variable component with negative slope which is identified to be of solar origin. The relatively constant increasing "residual" component at higher energies has been tentatively identified as being of modulated galactic origin. Certainly any increase in the particle flux with negative slope falling to the left of the relative minimum is likely to be of solar origin since the resultant spectra evolve smoothly and continuously into the more solar-active spectra when the particles can be positively related to solar features. The "residual" spectrum below 10 MeV is most likely of galactic origin because of its relative constancy, but a certain admixture of a constant solar component cannot be ruled out.

Several studies[3,4,7,8] have investigated low-energy solar cosmic-ray increases ($E < 20$ MeV/nucleon). These have shown that solar energetic particles are produced not only by large flares, but indeed are a characteristic feature of large "centers of activity" on the sun. Further, they also strongly suggest that particles are stored in the magnetic fields above certain active regions from where they diffuse into interplanetary space. The present study indicates that over the period of observation the low-energy cosmic rays are dominated by the solar component. In the previous studies during relative "quiet times" average spectra were obtained for periods of the order of several weeks. In several cases[1,2] these spectra were identified as being primarily of galactic origin, even though they contained the relative minimum discussed in the present study. It is asserted here that because of the dynamic nature of the low-energy component, such "quiet-time" spectra do not represent the true galactic background component, but that the low-energy turnup represents the variable solar component averaged over that period. It is expected that in continuing this analysis over a large period comparable with the solar cycle a second-order modulation of the residual component will be observed.

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