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OBSERVED DISTRIBUTION FUNCTIONS OF H, He, C, O, AND Fe IN COROTATING ENERGETIC PARTICLE STREAMS: IMPLICATIONS FOR INTERPLANETARY ACCELERATION AND PROPAGATION

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ABSTRACT

Distribution functions for H, He, C, O, and Fe derived from our IMP 8 measurements of ∿0.15 to ∿8 MeV/nucleon particles in three corotating streams observed near earth are shown to have a simple exponential dependence on the particle speed. The e-folding speed, v_o, is typically 0.01c, is found to be the same for the distribution functions of all elements examined, and varies little from one corotating event to the next. The relative abundances of energetic particles in these events resemble most closely the solar coronal composition and, thus, presumably that of the solar wind. These results may imply that the acceleration of these particles, which occurs in corotating interaction regions at several AU from the Sun, is by a statistical process.

Subject headings: interplanetary medium - Sun: solar wind - Sun: flares - cosmic rays: abundances

I. INTRODUCTION

Corotating or 27-day recurrent increases in the fluxes of $\lesssim$1 to ~20 MeV/nucleon protons and He were first observed in the interplanetary medium near earth during the 1965 solar minimum (Bryant et al., 1965; Fan, Gloeckler, and Simpson, 1965). These modest intensity increases last for several days and were found to be associated with high-speed solar wind streams and interplanetary magnetic field structure corotating with the Sun. Measurements of the radial gradient and anisotropies of particles in 27-day recurrent particle streams observed in the 1974-76 solar minimum have revealed that the peak intensity increases with heliographic radial distance (McDonald et al., 1976; Van Hollebeke et al., 1978, 1979; Kunow et al., 1977; Christon and Simpson, 1979), and that these particles diffuse inward (Mewaldt, Stone and Vogt, 1978; Ipavich et al., 1978; Ipavich, Gloeckler and Hovestadt, 1979). These results combined with the temporal-spatial correlations observed at ~4 to 5 AU between the ~1 MeV/nucleon corotating particle fluxes (Barnes and Simpson, 1976; Pesses, Van Allen, and Goertz, 1978) and the magnetic field and solar wind turbulence (Smith and Wolfe, 1976) in corotating interaction regions (CIR's) indicate the existence of large-scale and continuous particle acceleration in the interplanetary medium between ~2 and 5 AU. This acceleration could be the result of the turbulence which is generated when low- and high-speed solar wind streams collide (Fisk, 1976a, b) or it could occur at the forward and reverse shocks which bound the CIR's (Hundhausen and Gosling, 1976; Smith and Wolfe, 1976; Palmer and Gosling, 1978).

In this Letter we report measurements of the energy spectra and relative abundances of H, He, C, O, and Fe in three corotating particle streams observed near 1 AU during 1974 and 1976. We find that the distribution functions (particle number densities in phase space) derived from the energy spectra of the five elements studied all have a simple exponential dependence on particle speed over the entire range of the measurements, and that the e-folding or characteristic speed is the same for all elements within the experimental uncertainties. The relative abundances of the energetic particles in these events are found to be similar to the expected composition of the solar wind.

II. EXPERIMENT

Experimental results reported here were derived from data taken by the University of Maryland/Max-Planck-Institut Ultra Low-Energy Telescope (ULET) sensor on board the IMP-8 (*Explorer 50*) satellite. IMP-8 is in a nearly circular earth orbit at a geocentric distance greater than 25 earth radii. We have shown previously (Gloeckler *et al.*, 1976) that at these distances the geomagnetic field has no significant perturbing effect on the spin-averaged particle intensities in the energy range of the present measurements. The ULET sensor is based on the well-known energy loss-residual energy (dE/dx *vs* E) technique and measures both the nuclear charge and energy of the incoming particle. The use of a thin, flow-through proportional counter as the dE/dx element enables us to do the full two-parameter analysis for all data reported here. The large geometrical factor (0.53 cm sr) and low-energy response of ULET are essential for studies of heavy elements in corotating energetic particle streams. A detailed description of the ULET sensor has been previously reported by Hovestadt and Vollmer (1971).

III. OBSERVATIONS

Our results on the energy spectra of H, He, C, O, and Fe are presented in Fig. 1 for three well-known corotating particle streams observed during the 1974-76 solar minimum. Various aspects of these corotating events have been reported previously (Van Hollebeke *et al.*, 1978; Ipavich *et al.*, 1978; Scholer *et al.*, 1979; Christon and Simpson, 1979). In organizing our data we sought a representation which is a simple function of the particle energy (or momentum) and where the abundance ratios of the various elements remain constant. Plotted in Fig. 1 for each of the three corotating particle streams are the H, He, C, O and Fe distribution functions, $f = j/v^2$, (where j is the differential energy flux of the respective element) versus v, the particle speed in units of $(MeV/nuc)^{1/2}$. The individual data points are computed from one-day averaged differential energy fluxes in well defined energy intervals and plotted at exponentially weighted mean speeds corresponding to the given energy interval. For display purposes we have normalized the distribution functions of H, He, O and Fe to C except for the 1976, March 16 event where H is separated from the rest. The normalizations (or relative abundances) of each of the elements relative to C are given in Table 1.

The striking feature of the data presented in Fig. 1 is the exceptionally good fit of the distribution functions to simple exponentials in velocity (Gloeckler, 1979) over the entire range of the measurements, $0.4 \lesssim v \lesssim 3$ $(MeV/nuc)^{1/2}$, and six decades of intensity. Although previously reported representations of the energy spectra of protons and alpha particles as exponentials in momentum per nucleon (Van Hollebeke et al., 1978) or rigidity (Mewaldt, Stone and Vogt, 1978) and of He, C, O, Ne, and Fe as exponentials in kinetic energy per nucleon (Ipavich et al., 1978) provided reasonable fits to the experimental data above 1 MeV/nuc, it was not possible to accomodate the <1 MeV/nuc H and He observations in any of these other representations (Ipavich et al., 1978). Another remarkable feature is that the e-folding or characteristic speeds, v_0, are nearly equal for all elements in a given corotating event and that v_0 changes little from one event to the next. A typical value for v_0 is 0.2 $(MeV/nuc)^{1/2}$ or $3 \cdot 10^8$ cm/sec.

The distribution function for protons in the 1976, March 16 event (Fig. 1c) has been obtained over the wide energy (or velocity) range by combining our data below ~1 MeV with that reported by Van Hollebeke et al. (1979) at higher energies. The distribution function for protons is seen to have the characteristic exponential dependence and an e-folding velocity identical to that of He and the other elements. We also find that distribution functions computed from the energy spectra of ~1 to 10 MeV protons in a large number of corotating particle streams studied by the Goddard group (Van Hollebeke, et al., 1978, 1979; McGuire, von Rosenvinge, and McDonald, 1978), and by Caltech (Mewaldt, Stone, and Vogt, 1978) also have an exponential form with characteristic velocities in the 0.15 to 0.25 $(\mathrm{MeV/nuc})^{1/2}$ range. In contrast to the results presented here, distribution functions derived from the energy spectra of helium $\gtrsim$1 MeV/nucleon reported by the Caltech and Goddard groups have characteristic velocities which are generally 10 to 40% smaller than those of all the other elements examined. This apparent discrepancy in the helium measurements has not yet been resolved.

Using our ULET data we have examined the spatial-temporal evolution in the distribution function of helium in a number of corotating particle streams. Our results for the corotating particle stream in 1974 June 26-30 are shown in Fig. 2 where each distribution function is computed from one-day averaged energy spectra in the manner described above. Notice that on June 25, prior to the corotating increase, and on June 30, the last day of the increase f deviates from a simple exponential below ~0.8 $(\mathrm{MeV/nuc})^{1/2}$. At all other times, however, the exponential dependence on velocity is preserved, although there is a gradual but definite increase in the characteristic velocity from a value of 0.18 to 0.26 $(\mathrm{MeV/nuc})^{1/2}$. The results shown here are typical. We have found similar evolutions in the distribution functions of helium in a number of other corotating streams, and Van Hollebeke et al. (1979) also report a systematic flattening in the proton spectrum with time in recurrent events seen at earth. It should be pointed out that the shapes of event-averaged spectra are likely to be somewhat distorted because of the observed changes in the e-folding speed of the distribution function in the course of a corotating event.

IV. DISCUSSION

The spectral form of the distribution function found here ($f \propto \exp(-v/v_o)$) has several interesting properties and implications. First, this spectral form should be preserved as the particles propagate through the solar wind. We assume here that the particles are accelerated in or near the CIR, at several AU from the Sun, and then propagate back to earth along magnetic field lines without further acceleration. During this propagation, the behavior of f should be governed by the standard equation for the modulation of galactic cosmic rays (Fisk et al., 1973):

$$-\frac{v}{3}\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 V)\frac{\partial f}{\partial v} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 K_{||}\cos^2\psi\frac{\partial f}{\partial r}\right) - V\frac{\partial f}{\partial r} \qquad (1)$$

where we assume that there are no pronounced time variations in the energetic particle streams. Here, r is heliocentric radial distance, V is the solar wind speed, $K_{||}$ is the spatial diffusion coefficient for propagation along the mean magnetic field $\underline{B}_o$, and ψ is the angle between $\underline{B}_o$ and $\underline{r}$. It is observed that $K_{||} \propto v$ for low-energy particles (i.e., it is independent of rigidity), and that $K_{||}$ is sufficiently large so that the last term on the right in Eq. (1) can be neglected (e.g., Zwickl and Webber, 1978). With this approximation it can be readily shown that Eq. (1) entertains a solution of the form $f = f_1(r)\exp(-v/v_o)$, where $f_1(r)$ is a function of r only. This result is compatible with the Goddard observations that the spectral form in these events is essentially unchanged between the Helios, IMP, and Pioneer spacecraft (Van Hollebeke et al., 1979). This result also implies that our observed spectral form at 1 AU is representative of the spectral form in the region of acceleration near or in the CIR's.

Furthermore, the observed spectral form is compatible with a statistical mechanism as the dominant accelerating process operating in the CIR. Statistical acceleration is a diffusion in momentum (or velocity), and as such tends to yield spectra which are exponentials in various powers of the momentum. In fact, the momentum dependence of the solution for statistical acceleration in the solar wind presented by Fisk (1976a) is

$$f \propto \exp\left[-\frac{V}{3r}\frac{(7-2\beta)}{(2-\beta)^2}\frac{p^2}{D_{pp}}\right], \qquad (2)$$

where $D_{pp} = D_o p^\beta$ (D_o and β are constants) is the diffusion coefficient in momentum. Clearly if $p^2/D_{pp} \propto v$ the spectral form in Eq. (2) is identical to the observed spectral form. This requirement on the velocity dependence of D_{pp}, as well as the requirement that the magnitude of D_{pp} is sufficient to yield the observed v_o, will place constraints on possible statistical mechanisms.

The observed spectral form appears to be less compatible with a mechanism in which the dominant acceleration occurs at the forward and reverse shocks which bound the CIR. At least in their simple forms, shock acceleration mechanisms tend to yield spectra which are power laws in energy (e.g., Axford et al., 1977).

The observed composition in these events also has implications for the accelerating process. As can be seen in Table 1, the relative abundance of the elements in corotating particle streams resembles the composition of the solar corona, and thus presumably the solar wind, as opposed to the composition of solar flare particle events. It appears, then, as if the particles are being accelerated directly from the solar wind, or its suprathermal tail. This result is compatible with a statistical mechanism since here particles are accelerated provided that their speed exceeds the Alfven speed (e.g., Fisk, 1976a). In the solar wind the Alfven speed is comparable to the ion thermal speed.

In constrast, the threshold speed for a shock-acceleration mechanism can be well above solar wind thermal speeds. For shock acceleration to be efficient, particles must make multiple interactions with the shock front. Equivalently, after interacting with the shock the particles must have sufficient speed to propagate upstream in the solar wind, where they can be reflected back to the shock for further energization (e.g., Fisk 1971, Palmer and Gosling, 1978). Since the magnetic field in these events can be closely aligned with the shock fronts, the required speed of the particles to execute this process is relatively high.

We note finally that the increase in v_o with time during an event, which is shown in Fig. 2, may imply that the efficiency of the acceleration process increases with heliocentric radial distance. As an event observed at earth progresses one is sampling the distribution function of the energetic particles further along the CIR because the magnetic field lines at earth connect to the CIR at progressively larger radial distances (e.g., Hundhausen and Gosling, 1976).

V. CONCLUDING REMARKS

We have reported here that energetic particles in several corotating particle streams have a simple spectral form, $f \propto \exp(-v/v_o)$, and a composition which resembles the expected composition of the solar wind. Both of these results are compatible with a statistical mechanism as the dominant accelerating process for these particles.

It should be noted, however, that there are also difficulties with statistical mechanisms. Barnes and Simpson (1976) report, from Pioneer observations, that the particle events tend to peak near the edges of the CIR, where the forward and reverse shocks are located, and that in general more particles appear to be accelerated at the trailing edge of the CIR. There is also a pronounced increase in the proton to helium ratio at the forward shock or leading edge of the CIR (Barnes and Simpson, 1976). In addition one finds that corotating particle increases at earth are entirely contained within the high-speed solar wind streams (e.g. Scholer et al., 1979) which connect to the reverse shock in the CIR. It is not obvious why a statistical mechanisms should produce such results.

Clearly, there is a need for more detailed observations and for more theoretical studies. It would be useful to observe simultaneously the composition of the solar wind and the energetic particles in these events to confirm that the solar wind is the source of the particles. It would also be helpful to have detailed measurements of solar wind turbulence in the CIR for use in building a statistical acceleration theory. Finally, there is a need for detailed modeling calculations of the acceleration process.

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Table I

Relative Abundances of Elements in Corotating Particle Streams, the Solar Corona, and Solar Flare Particle Events

	Corotating Particle Streams[a]					Solar Flares	
Element	Jun 27	Aug 20	Mar 16	Average	Solar Corona[b]	Normal[c] (1-20)	Fe-rich[d] (1-4.6)
H	2000	2000	2040	2015	1780	8500	1300
He	133	140	170	150	100[e]	130	175
C	≡1	≡1	≡1	≡1	≡1	≡1	≡1
O	1.0	1.0	1.0	1.0	1.0	1.85	>4
Fe	0.13	0.087	0.057	0.09	0.09	0.28	>5.5

(a) These normalization factors are applied to the measured distribution functions of H, He, O and Fe over the range of the measurement. The normalized distribution functions are plotted in Fig. 2.

(b) Withbroe (1971)

(c) Gloeckler (1979); Approximate energy ra[illegible] (in MeV/nuc) of measurements is indicated in parenthesis.

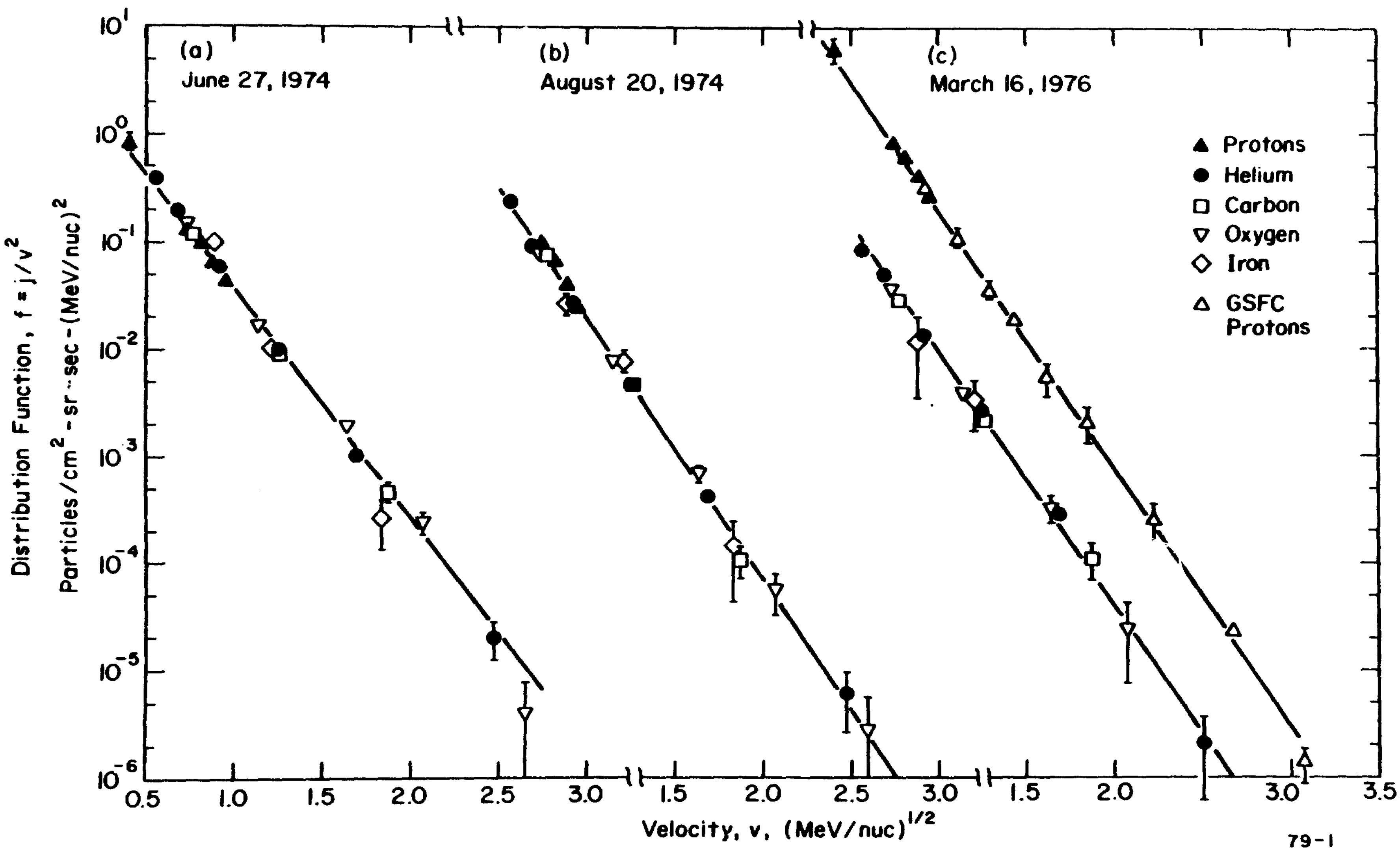
(d) Mason *et al*. (1979).

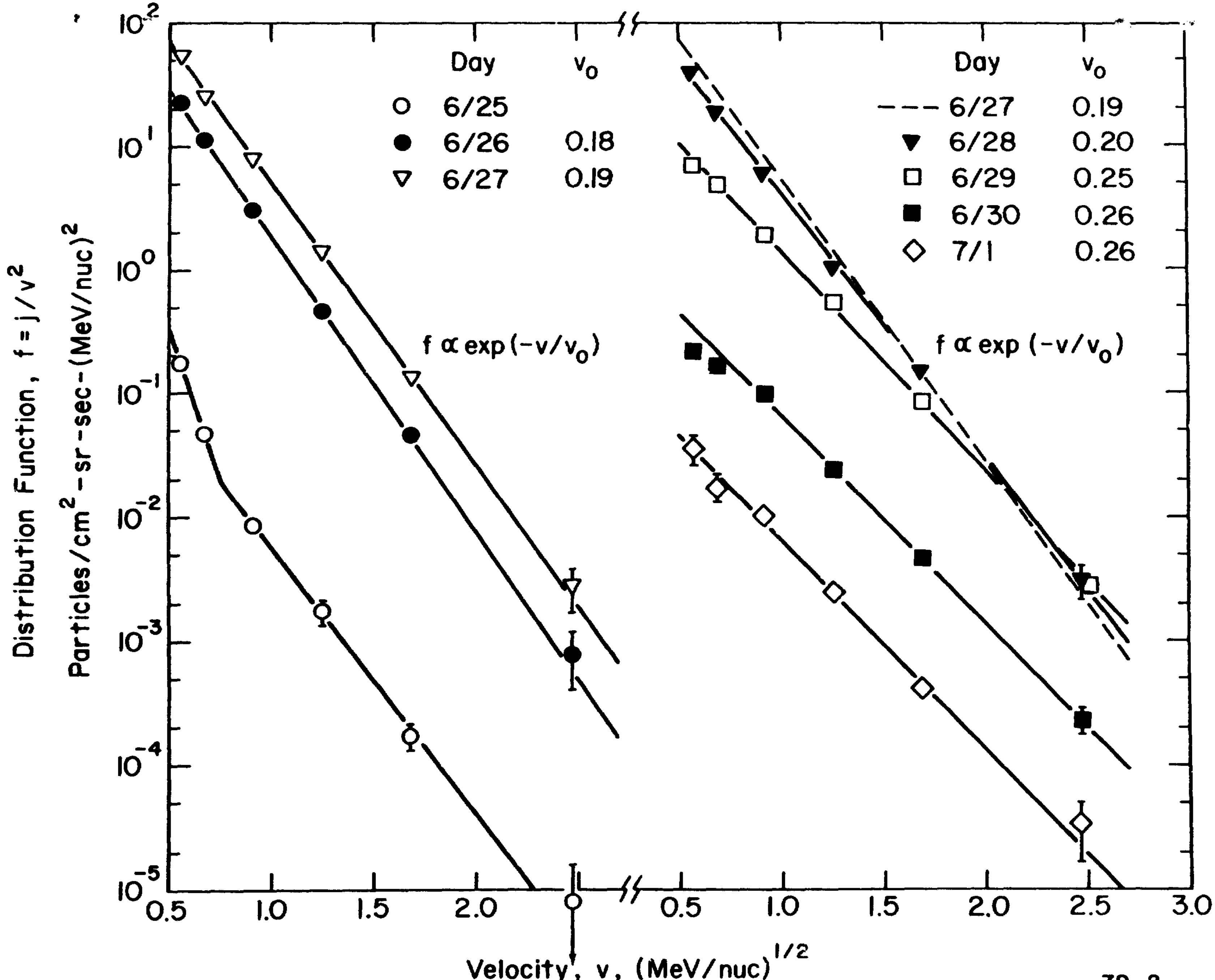
(e) Bame *et al*. (1977).

Figure Captions

Figure 1 Normalized distribution functions of H, He, C, O and Fe derived from one-day averaged energy spectra observed during peak intensities in three corotating streams: (a) 1974, June 27, (b) 1974, August 20, and (c) 1976, March 16. The distribution functions for protons (▲), helium (●), oxygen (▼) and iron (◆) have been normalized to carbon (■) except in the 1974, March 16 event where for purposes of display the proton distribution function based on present work (▲), and on data of Van Hollebeke et al. (△) has been separated by a factor of 20 from the other elements. The proton points at 0.4 (MeV/nuc) have been estimated using the one-day averaged 0.13 - 0.21 MeV rate of the University of Maryland EECA sensor (Tums et al., 1974). The normalization factors used are given in Table 1. Notice the exponential dependence on particle speed, and the lack of significant variability in the e-folding velocities.

Figure 2 Distribution functions of helium in the 1974 June 26-30 corotating event observed near earth. During the corotating increase the distribution functions are exponentials in velocity. The e-folding speed, v_o, increases systematically with time. The exponential form of the distribution function is still observed on July 1, when the 0.5 to 1.5 MeV proton intensity has dropped below its value prior to the corotating increase.


Distribution Function, f = j/v^2
Particles/cm^2-sr-sec-(MeV/nuc)^2
(a)
June 27, 1974
(b)
August 20, 1974
(c)
March 16, 1976
Protons
Helium
Carbon
Oxygen
Iron
GSFC Protons
Velocity, v, (MeV/nuc)^1/2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0.5
1.0
1.5
2.0
2.5
3.0
3.5
79-1



Distribution Function, f = j / v2
Particles / cm2 - sr - sec - (MeV/nuc)2
Day
v0
6/25
6/26
0.18
6/27
0.19
f α exp (-v/v0)
Day
v0
6/27
0.19
6/28
0.20
6/29
0.25
6/30
0.26
7/1
0.26
f α exp (-v/v0)
Velocity, v, (MeV/nuc)1/2

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