NASA

Technical Memorandum 78105

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(NASA-TM-78105) THE COMPOSITION OF COROTATING ENERGETIC PARTICLE STREAMS (NASA) 25 p HC A02/MF A01 CSCL 03B

N78-21039

Unclas

G3/93 12577

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MARCH 1978

National Aeronautics and
Space Administration

Goddard Space Flight Center
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THE COMPOSITION OF COROTATING ENERGETIC PARTICLE STREAMS

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ABSTRACT

The relative abundances of 1.5 - 23 MeV/nucleon ions in corotating nucleon streams are compared with ion abundances in particle events associated with solar flares and with solar and solar wind abundances. He/O and C/O ratios are found to be a factor of the order 2-3 greater in corotating streams than in flare-associated events. The distribution of H/He ratios in corotating streams is found to be much narrower and of lower average value than in flare-associated events. H/He in corotating energetic particle streams compares favorably both in lack of variability and numerical value to H/He in high speed solar wind plasma streams. This comparison suggests that the source population for the corotating energetic particles is the solar wind, a suggestion consistent with acceleration of the corotating particles in interplanetary space. The near numerical equality of H/He values appears to indicate a rigidity independent acceleration rate.

I. INTRODUCTION

Periods of enhanced MeV nucleon flux corotating with the interplanetary magnetic field have been the object of recent study (McDonald et al., 1976; Barnes and Simpson, 1977; Marshall and Stone, 1977; Van Hollebeke et al., 1977; Pesses et al., 1978). The streams are characterized by a lack of velocity dispersion in the time of peak particle fluxes, by a lack of optical flare, X-ray or radio burst association, by recurrence in successive solar rotations at time intervals appropriate to a geometry corotating with the interplanetary magnetic field over a wide range of radial distances, by steep energy spectra, by positive radial gradients, and by inward pointing anisotropies in the frame of the solar wind. McDonald et al. (1976) argued that increases in stream particle flux seen at Pioneer (3-5 AU) compared to IMP 7 (at 1 AU) are evidence for interplanetary acceleration of these particles somewhere beyond 1 AU, an interpretation supported by the anisotropy measurements of Marshall and Stone (1977).

A preliminary comparison of corotating stream composition with flare particle composition (McGuire et al., 1977) suggested the existence of some systematic differences. Several other studies (Zwickl et al., 1977; Scholer, 1977) qualitatively support the existence of these differences. We now present more comprehensive data on the composition of corotating particle streams at 1 AU as contrasted with energetic solar particle composition and with solar and solar wind abundances. Two additional papers (McGuire et al. 1978a, b -- hereafter Papers II and III) will discuss in more detail solar particle spectra and composition.

II. EXPERIMENT

The Goddard cosmic ray experiments on the satellites IMP 7 and IMP 8 are the source for data reported here. The IMP 7 and IMP 8 low-energy-detectors (LED's) are telescope assemblies composed of two pulse-height analyzed Si solid-state detectors (150μ and 2.7mm thickness) with a surrounding plastic scintillator for active anti-coincidence. The instruments are essentially identical to the LED flown on IMP 6 and described in detail by Teegarden et al. (1973). The IMP 8 very-low-energy-telescope (VLET) consists of three pulse-height analyzed Si detectors (two of 35μ and one of 1mm thickness) plus an anti-coincidence detector. Both LED and VLET telescopes separate ions through Fe by measurements of differential energy loss rate dE/dx and total energy E. The IMP 8 VLET allows dE/dx-E analysis to lower energies than do the LED's because the detectors are thinner, although the LED's have larger geometrical factors (0.39 versus 0.16 cm^2-ster) and allow a total E measurement of particles stopping in the front detector. Both telescope systems operate with data systems which assign readout priority to certain dE/dx-E regions, thus allowing adequate sampling of ions beyond He and at higher energies during high flux periods (see Teegarden et al. 1973).

Full dE/dx-E analysis of ions in the CNO group can be performed only above 3 MeV/nucleon in the VLET and above 8 MeV/nucleon in the LED's. These energy limits are too high to give useful count statistics in the study of corotating energetic particle streams or many small flare events. To expand the data base for such study, we include particles stopping in the front LED sensor (the A detector) in the analysis. The LED A detector geometry is completely defined by the plastic anti-coincidence cup and the total E detector so that the flux of particles stopping in the A detector is accurately determined. While we have a measure of total ion energy, we can define only a lower limit to the ion charge of particles stopping in the A detector. The lower limit exists because the maximum total energy of a particle which will stop in the A detector is lower for particles with less charge and/or mass. Thus in the lowest A detector channels, ions from H to Fe will contribute to the measured flux while in higher channels only ions C to Fe, for example, might contribute. A complication in the analysis is that the heavier nuclei in a given A detector channel will have smaller energy/nucleon values than lighter nuclei in the same channel. Thus, because flux usually falls with increasing ion energy, the contribution of heavier ions will become more important. Nonetheless, in the lowest A detector channels, the abundance of H relative to He or CNO is sufficiently large in most particle events that H dominates in these channels. Similarly a range of A channels above the energy at which H penetrates the A detector exists where He commonly dominates. No such simple separation of ions heavier than He is possible for A detector channels above the He penetration energy (C through Fe abundances are in general too similar) and some composite intensity measure is all that can be constructed. This combined C through Fe flux is determined both by the relative abundances and by the shapes of the C through Fe energy spectra.

The composite medium and heavy ion flux constructed from the LED A detector data is properly normalized on a per MeV basis. For convenience, we instead normalize this flux as if all the ions were Oxygen, thus obtaining a flux normalization as MeV/ nucleon to compare with O, H or He fluxes. A comparison of the C through Fe composite flux (which we will term a flux of ZCOMP particles) with the flux of true O ions for selected time periods is shown in Figure 1. The solid and open circles are experimental points based on relative VLET and LED measurements in large events where substantial Fe/O ratios were or were not observed. Any question regarding absolute flux normalization in the comparison is resolved by working with the ratio in the form He/O (VLET)/ He/ZCOMP (LED) = ZCOMP (LED)/ O (VLET). P_o is a characteristic momentum/nucleon based on a fit of the He spectrum to a form

$$dJ/dP = A \exp (-P/P_o)$$

with P and P_o in units of MeV/c/nucleon. Predicted ZCOMP/O ratios for two different relative compositions are shown by the curves, with P_o assumed independent of ion charge in the calculations. Smaller P_o produce larger ZCOMP/O ratios as do enhanced heavier ion fluxes, both experimentally and in the calculations. The relative contribution of the three major groups C-N-O, Ne-Mg-Si and Fe to the ZCOMP flux will vary with relative abundances on an energy/nucleon basis and spectral shape. Observed VLET Fe/O ratios and the absence of large (>7) ZCOMP ratios in Figure 1 suggest a tendency toward small Fe/O ratios in events with steep spectra. Under this assumption, no one of the groups C-N-O, Ne-Mg-Si or Fe will dominate (contribute >50% to) the ZCOMP flux.

III. OBSERVATIONS

The time and energy resolution of the Goddard experiments are limited by count rate statistics. Thus the level of analysis which can be performed depends strongly on the size and spectral properties of a given particle event at 1 AU. The steepness of ion spectra in corotating energetic streams is a severe constraint on the statistics of the analysis, particularly for particles heavier than He. Generally, only event-averaged composition with limited energy resolution can be obtained. The effects of using event-averaged spectra and fluxes rather than true peak spectra in the flare events is discussed in Paper II and found to be small in the application presented here. Individual recurrences of streams generally have broad maxima such that event averages present no complications.

For the purposes of this study, corotating energetic particle streams in the IMP data set have been identified by the absence of particle velocity dispersion or flare association and by the recurrence of the enhanced fluxes with $\sim$27-day periodicity. Many of the events can additionally be identified in Pioneer and/or Helios data with appropriate corotation delays (cf., McDonald et al., 1976; Van Hollebeke et al., 1977). Conversely, flare-associated events are identified by the presence of velocity dispersion in the arrival of particles and by temporal association with optical flares and X-ray and/or radio bursts.

The survey covers the period October 1972 to December 1976. Tabular listings of all flare and corotating events will be included in Paper II.

Statistics in the corotating events are generally such that only H and He spectral slopes can be examined. The spectra of corotating events are generally better fit by exponentials in momentum/nucleon with similar spectral slopes for H and He (see also Van Hollebeke et al., 1978). Flare spectra are sometimes better fit by exponentials in momentum/nucleon and sometimes by power laws in energy, although over a narrow energy range such as 2-10 MeV/nucleon neither approximation is grossly in error. In Figure 2, the characteristic momentum P_o values for He spectra in flare and corotating events are contrasted. The steepness of the corotating nucleon stream spectra (small P_o values) is apparent. Peak flux spectra of the flare events would generally be even flatter than indicated in the histogram.

In Figure 3 we contrast C/O, He/O, He/ZCOMP and H/He abundances between flare-associated events and corotating streams. Only events with clear classification (i.e. flare, corotating) have been included in the histograms. The histograms indicate the following trends:

1. C/O is larger for corotating than for flare-associated events by a factor $\sim$2.
2. He/O and He/ZCOMP ratios are consistent with each other. They are larger by factors $\sim$2.5 for corotating as opposed to flare-associated events.

3. H/He is smaller and much less variable in corotating than in flare-associated events.

The average ratios and the number of sample periods entering into each histogram are given in Table 1. We recall that ZCOMP represents a sum of ion intensities over the range C to Fe, a sum that with "normal" abundances and at the same MeV/nucleon would be a factor 2 greater than the O intensity. A difference $\geq$ 2 between He/O and He/ZCOMP ratios for either flare events or corotating streams is then reasonable and quantitatively consistent with the calculations shown in Figure 1. We note, however, that the number of sample periods contributing to the determination of C/O and He/O for corotating streams is quite small. The greater number of stream encounters that could be used in the He/ZCOMP data thus increases the credibility of the differences seen in He/O between flare events and corotating streams. These differences in He/ZCOMP cannot be attributed to the steeper spectra of the stream particles. To demonstrate, Figure 4 shows the individual experimental He/ZCOMP ratios plotted versus the slope P_o of an exponential spectral fit to He for all LED events studied (both flare and corotating). In calculations similar to those entering Figure 1, curves showing the predicted P_o dependence of He/ZCOMP overlay the experimental data in Figure 4. All ions are assumed to have the same spectral shape. The calculated curves have been normalized by adjusting the He/O ratio such that theory and experiment are consistent for flat spectra (large P_o). That the calculated curves then show a trend with decreasing P_o opposite to the experimental data clearly shows the existence of real composition differences. It should be noted again that the effect of using event-average as opposed to peak-flux spectra is not large on the scale of the histograms.

Zwickl et al., (1977) show H/He ratios at 3 MeV/nucleon of 18^{+22}_{-6} for what they term small spatial events (events showing no time dispersion or rapid onset, Gold et al., 1977). The maximum limits of variation in the Goddard data (H/He ranging from 16 to 29 in 17 events) also differ from Zwickl et al. (1977) limits (H/He ranging from 6 to 100 in 42 events). We believe the differences are most likely the effect of more stringent selection criteria used in the Goddard sample to define corotating events, primarily the 27-day recurrence requirement. We thus believe that no contradiction exists between our results and those of Zwickl et al. (1977).

IV. DISCUSSION

We are concerned with questions of where and from what population the corotating stream nucleons are accelerated and by what mechanisms they are accelerated. As a summary of relevant composition data, we compare the experimental average abundances with comparable universal (Cameron, 1973), solar atmosphere (Webber, 1975) and solar wind abundances (Bame et al., 1975, 1977) in Table 1. The most important comparisons are those of the H/He ratios. We note two major points. First, the variability in H/He ratios in corotating energetic ions is grossly different from that of flare-associated ions. Corotating event H/He variability is essentially identical to that of H/He ratios in the solar wind, particularly ratios taken within high speed solar wind streams. Second, the numerical value of H/He in the corotating streams is almost identical to H/He in the high speed solar wind plasma streams (Bame et al., 1977).

The common lack of variation in H/He of the corotating energetic particles and the solar wind plasma suggest that a possible source population for the energetic particles is the solar wind plasma. This hypothesis is supported by the near numerical equality of the average H/He ratio in these populations. Conversely, the great difference in variability between flare and corotating H/He ratios suggests differences either in source populations or in the acceleration mechanisms and propagation effects between flare and corotating energetic particles.

Assuming that the solar wind is the parent particle population, the equality of ratios implies a charge to mass (q/m) or rigidity-independent acceleration mechanism. Two possible interplanetary acceleration mechanisms cited by McDonald et al. (1976) for corotating particles are second-order Fermi acceleration by Alfven discontinuities at stream-stream interaction regions (Jokipii, 1971; Wibberenz and Beuermann, 1971) or acceleration by long wavelength magnetosonic waves at heliocentric distances beyond 1 AU, (transit time damping). The latter was proposed by Fisk (1975) as part of an explanation for anomalous quiet-time composition at 10 MeV (McDonald et al. 1974; Hovestadt et al. 1973; and others). A possible site for such wave acceleration is at the corotating shock boundaries (Barnes and Simpson, 1977; Pesses et al., 1978).

The Fermi acceleration rate will go as (Jokipii, 1971)

$$(dT/dt)_F \propto V_A^2\, T/\kappa_{\parallel}$$

for T the kinetic energy/nucleon, V_A the Alfven velocity in the solar wind (= the velocity of random scattering centers) and $\kappa_{\parallel}$ the parallel diffusion coefficient. Recent studies (Datlowe, 1971; Lanzerotti et al., 1973; Reinhard and Wibberenz, 1974; Van Hollebeke et al., 1974; McKibben et al., 1975; Zwickl and Webber, 1977a, 1977b; Ma Sung, 1977) find a radial diffusion mean free path independent of rigidity below $\sim 3\times10^2$ MV, corresponding to proton energies <25 MeV/nucleon. Thus Fermi acceleration is independent of q/m (since $\kappa_{\parallel} \propto \lambda$). Later development of the transit time damping model (Fisk, 1976a, b, 1977a), on the other hand, shows a rate of acceleration

$$\frac{dT}{dt}_{TTD} = \frac{D_{TT}}{T^2}\,\frac{T}{2} \propto \frac{V_A^2}{V}\,\frac{\overline{\delta B}^2}{B_0}\,(r_g\lambda_Z)^{-1/2}\,T.$$

D_{TT} is a diffusion coefficient in energy space, B_0 and $\overline{\delta B}$ the interplanetary magnetic field strength and the perturbations due to magnetosonic waves, λ_Z the scale length along the field for interaction and r_g the particle gyroradius. This equation gives a rate of acceleration proportional to $(q/m)^{1/2}$, which is at first appearance inconsistent with the IMP measurements. However, among other possibilities, it should be noted that the corotating stream acceleration could be in a saturation limit of the Fisk model, where the relative abundances in the parent solar wind population rather than the rates of acceleration determine the relative H and and He abundances (Fisk, 1977b). We also note that

Fisk (1976a, b) has pointed out serious numerical difficulties in producing corotating energetic particles via the Fermi model without invoking very small mean free path lengths (.003 AU) in the interplanetary medium.

Solar wind composition data for ions heavier than He is limited and highly uncertain; thus, we do not believe that useful comparison of this data with corotating energetic ion stream abundances is possible at present. Consistency in heavier ion abundances between the solar wind plasma and corotating stream particles will eventually prove a key test of the suggestions both that the solar wind plasma is the parent population and that the acceleration is rigidity independent.

Acknowledgements

The authors thank M. A. I. Van Hollebeke for helpful comments on this work.

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FIGURE CAPTIONS

Figure 1. Helium spectral slope P_o for a form exponential in momentum/nucleon ($dJ/dP = A \exp(-P/P_o)$ with P and P_o in MeV/c/nucleon) versus ZCOMP (from the LED's and O(from the VLET) fluxes. Points are separated on the basis of Fe/O ratios seen in the VLET. The two curves are theoretical predictions of the P_o dependence. Relative composition 1 has C = 0.4, N = 0.125, O = [illegible].0, Ne = 0.175, Ng = 0.25, Si = 0.15, S = 0.0[illegible], Ca = 0.01, Fe = 0.2. Relative composition 2 has C, N, O the same as above; Ne, Mg, Si scaled down by [illegible].8; S, Ca, Fe = 0.0.

Figure 2. A histogram showing the distribution of P_o values for flare event and corotating stream Helium spectra. The study covers the period October 1972 to December 1976. Only events with a clear classification as flare or corotating have been included in this and the subsequent histograms.

Figure 3. A group of four histograms showing the distribution of ratios for VLET C/O and He/O flux and LED He/ZCOMP and H/He flux. Light lines correspond to flare events, dashed lines to corotating streams. Off-scale events have been grouped in the last bin of each histogram and are indicated by the horizontal arrows.

Figure 4. Helium spectral slope P_o versus observed He/ZCOMP flux ratios. The two curves are theoretical predictions in the manner of Figure 1. Composition 1 and 2 are the same as in Figure 1. Points in parenthesis are uncertain as to classification (flare or corotating). Points without symbols could not be even tentatively classified as flare or corotating events. Triangles indicate events with enhanced He^3/He^4 ratios.

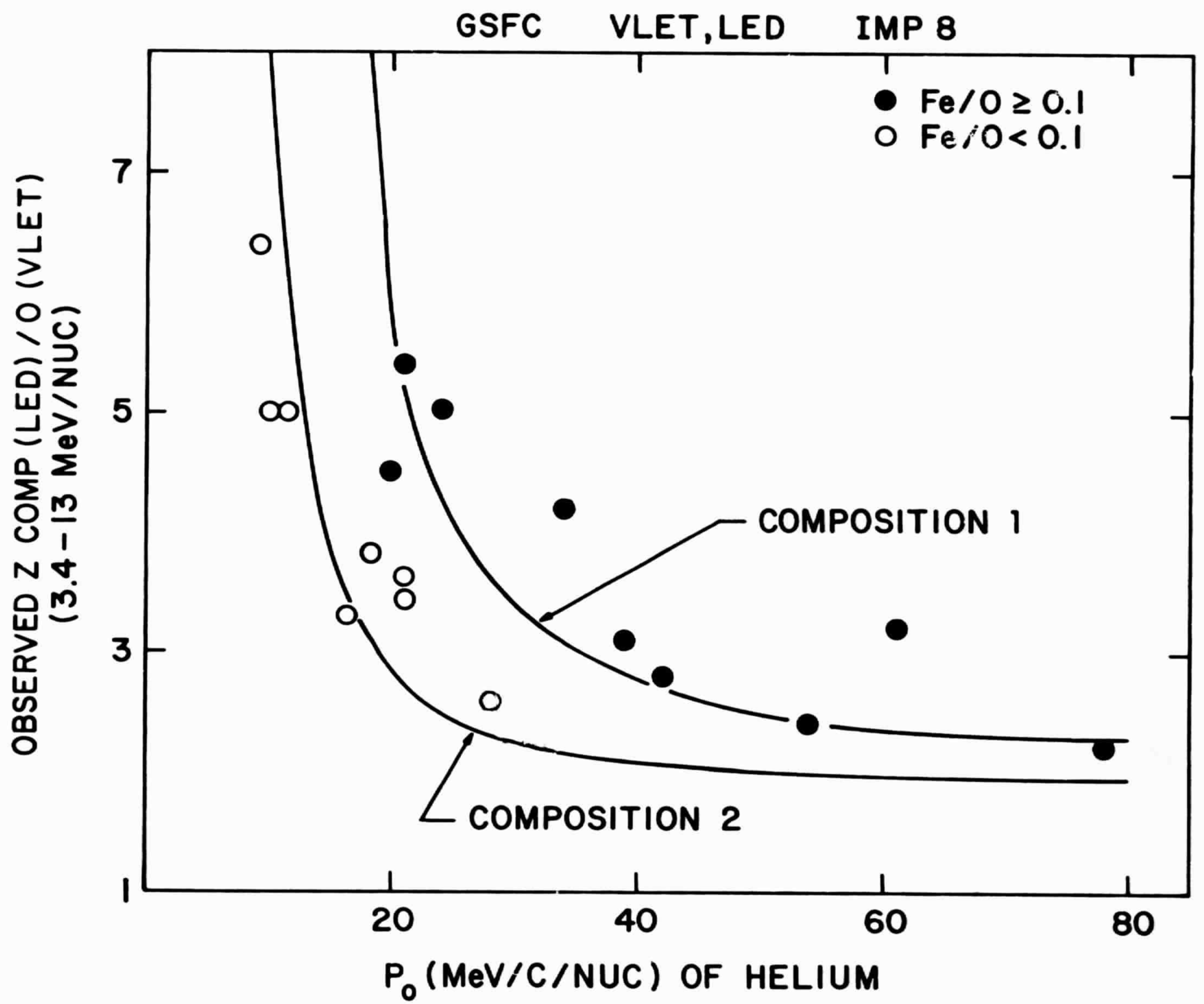
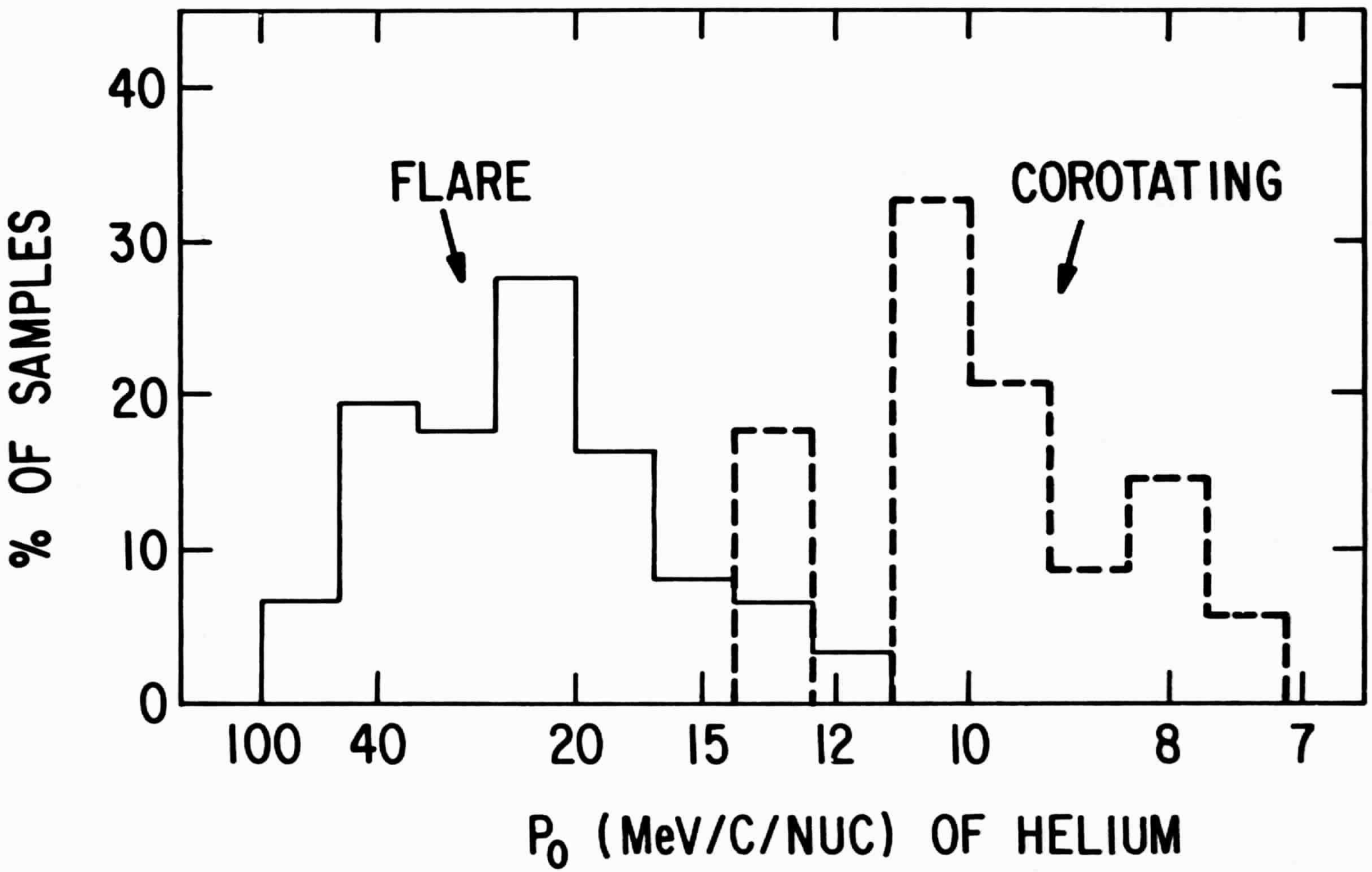

GSFC VLET, LED IMP 8
Fe/O ≥ 0.1
Fe/O < 0.1
COMPOSITION 1
COMPOSITION 2
OBSERVED Z COMP (LED) / O (VLET)
(3.4 – 13 MeV/NUC)
7
5
3
1
20
40
60
80
P0 (MeV/C/NUC) OF HELIUM

Fig. 1



% OF SAMPLES
40
30
20
10
0
FLARE
COROTATING
100
40
20
15
12
10
8
7
P0 (MeV/C/NUC) OF HELIUM

Fig. 2

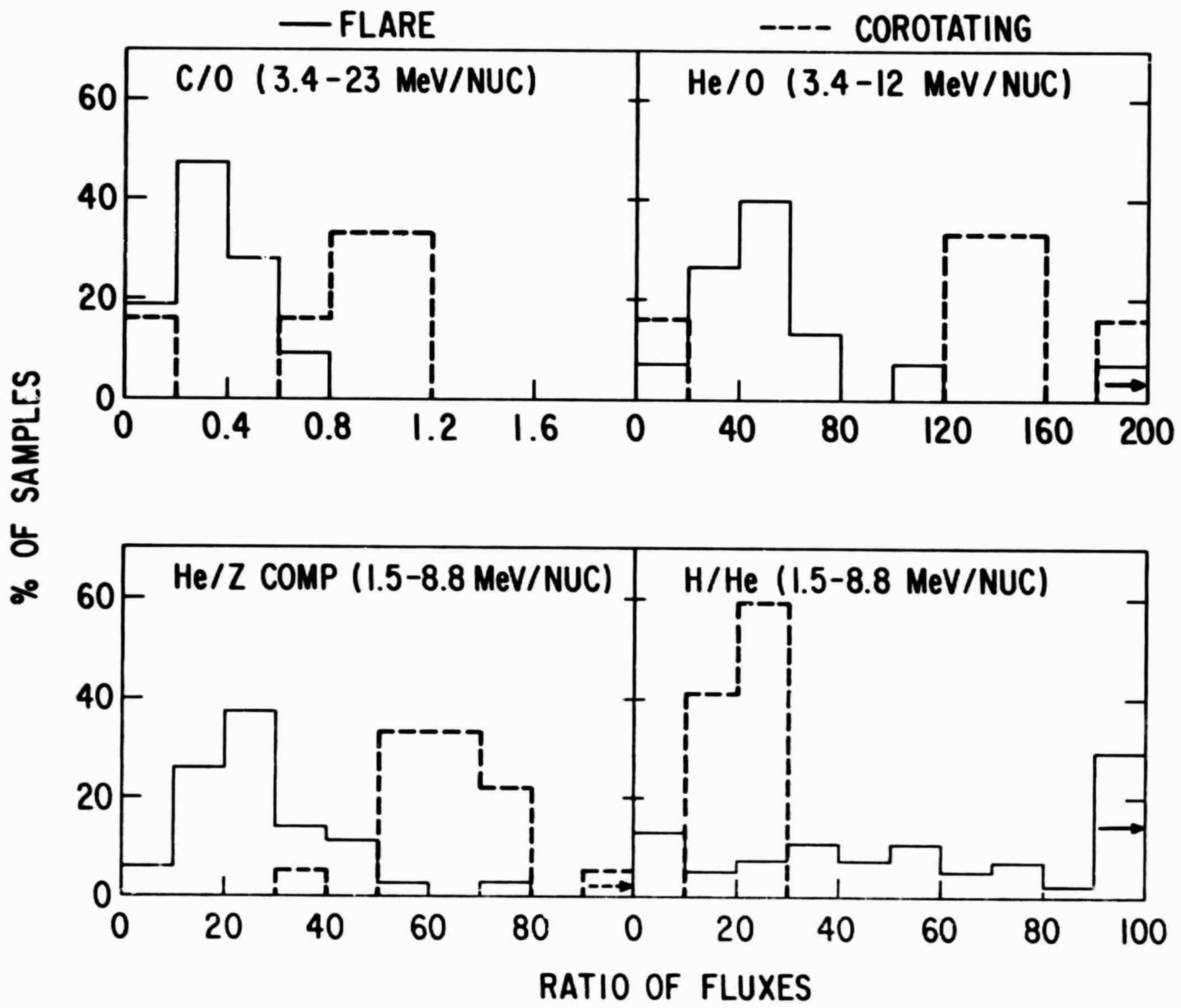

—— FLARE
---- COROTATING
% OF SAMPLES
C/O (3.4-23 MeV/NUC)
He/O (3.4-12 MeV/NUC)
He/Z COMP (1.5-8.8 MeV/NUC)
H/He (1.5-8.8 MeV/NUC)
0
20
40
60
0
0.4
0.8
1.2
1.6
40
80
120
160
200
20
60
100
RATIO OF FLUXES

Fig. 3

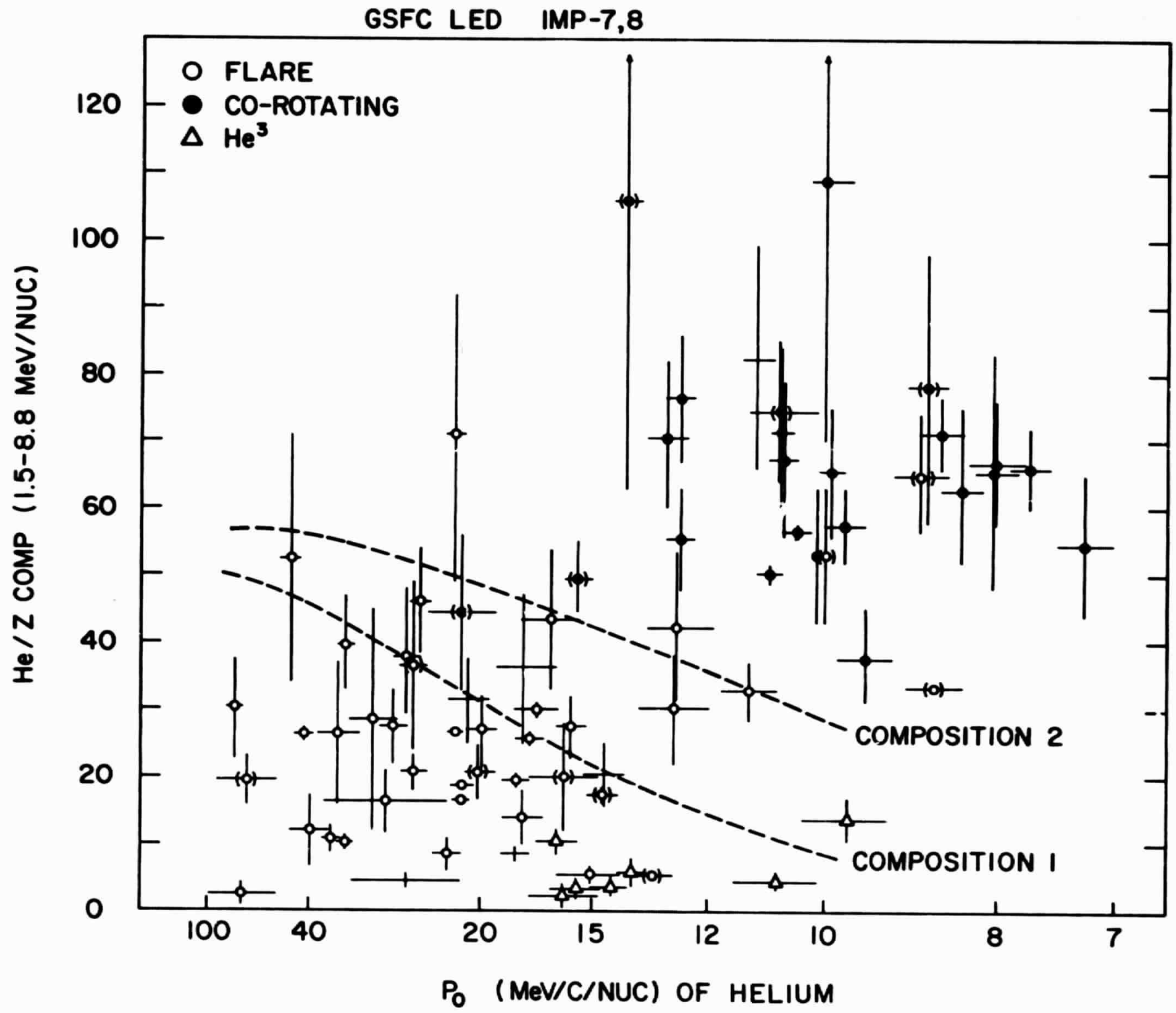

GSFC LED IMP-7,8
FLARE
CO-ROTATING
He3
He/Z COMP (1.5-8.8 MeV/NUC)
0
20
40
60
80
100
120
100
40
20
15
12
10
8
7
P0 (MeV/C/NUC) OF HELIUM
COMPOSITION 2
COMPOSITION I

Fig. 4

TABLE 1: AVERAGE COMPOSITION COMPARISON

	Co-Rotating Events		Flare Events			Solar	Solar Wind
	NO. OF EVENTS	ABUNDANCE	NO. OF EVENTS	ABUNDANCE	Universal (Cameron, 1973)	Atmosphere (Webber, 1975)	(Bame et al., 1975, 1977)
He/O (3.4-12 MeV/nuc)	6	130 ± 30	15	50^{+30}_{-20}*	102	270 ± 80	60^{+60}_{-30}**
C/O (3.4-23 MeV/nuc)	6	0.8 ± 0.2	16	0.37 ± 0.15	0.54	0.6 ± 0.1	--
H/He (1.5-8.8 MeV/nuc)	17	22 ± 5	38	56^{+100}_{-36}	14.4	--	21 ± 3***
He/ZCOMP (1.5-8.8 MeV/nuc)	18	64 ± 15	35	26 ± 14	(<50)	(<175)	(<60)**

( ) inferred from He/O

* median values

** primarily low speed plasma streams; also note the error bars may be larger than indicated.

*** high speed plasma streams only: low speed plasma streams H/He = 26 ± 10.

BIBLIOGRAPHIC DATA SHEET

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TM 78105		

4. Title and Subtitle	5. Report Date
The Composition of Corotating Energetic Particle Streams	March 1978
	6. Performing Organization Code: 660
7. Author(s): R. E. McGuire, T. von Rosenvinge, F. McDonald	8. Performing Organization Report No.
9. Performing Organization Name and Address: Code 660, Laboratory for High Energy Astrophysics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771	10. Work Unit No.
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
	14. Sponsoring Agency Code

15. Supplementary Notes

Submitted for publication to Astrophysical Journal (Letters)

16. Abstract

The relative abundances of 1.5 - 23 MeV/nucleon ions in corotating nucleon streams are compared with ion abundances in particle events associated with solar flares and with solar and solar wind abundances. He/O and C/O ratios are found to be a factor of the order 2-3 greater in corotating streams than in flare-associated events. The distribution of H/He ratios in corotating streams is found to be much narrower and of lower average value than in flare-associated events. H/He in corotating energetic particle streams compares favorably both in lack of variability and numerical value to H/He in high speed solar wind plasma streams. This comparison suggests that the source population for the corotating energetic particles is the solar wind, a suggestion consistent with acceleration of the corotating particles in interplanetary space. The near numerical equality of H/He values appears to indicate a rigidity independent acceleration rate.

17. Key Words (Selected by Author(s))	18. Distribution Statement
Interplanetary Acceleration, Energetic particles, interplanetary particle composition, corotating streams	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
		23	

*For sale by the National Technical Information Service, Springfield, Virginia 22151.

GSFC 25-44 (10/77)