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Corotating Energetic Particle and Fast Plasma Streams in the Inner and Outer Solar System - Radial Dependence and Energy Spectra

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Introduction

Corotating energetic particle events appear to be the major source of MeV protons in the outer heliosphere. In a recent paper, Van Hollebeke et al (1978) summarized the observations of these particle streams using the data from Goddard cosmic ray experiments on Helios, Pioneer and IMP. These studies covered much of the solar minimum period of cycle 20 and ranged from 0.30 to 10 AU. The main characteristics of this class of energetic particle events are:

1. The existence of a positive radial gradient of some +350% per AU between .3 AU and 1 AU, an average gradient of +100% per AU between 1 AU and 4 AU and a negative gradient of some -40% to -100% per AU beyond 4-6 AU (e.g. Van Hollebeke et al., 1978 and references therein).

2. The close association of those events with corotating interaction regions (CIR's) formed between high speed and low speed solar wind streams (McDonald et al., 1976; Barnes and Simpson, 1976; Pesses et al., 1978; Van Hollebeke et al., 1978).

The discovery of this positive radial gradient between 1 AU and 4 AU led McDonald et al., 1976 to propose interplanetary acceleration as the most plausible explanation for these events and to suggest the suprathermal distribution of the solar wind as a possible source of particles. Detailed studies on the association between corotating particle streams and corotating interaction regions (CIR's) which develop forward and reverse shocks beyond $\sim$1.5 AU (Hundhausen and Gosling, 1976; Smith and Wolfe 1976) have further pointed to the CIR's and their related shocks as a possible source of particle acceleration (Barnes and Simpson, 1976; Pesses et al. 1978). In support of particle acceleration near the boundary region where shocks are observed, Barnes and Simpson 1976 have shown: 1) In many cases, the positions of the double peaks in recurring proton intensity increases coincide with the forward and reverse shocks; 2) The energy spectrum varies greatly at the passage of the forward shock where the spectrum is the steepest; 3) The proton to alpha ratio varies near the passage of the forward shock with the ratio being the largest at the forward shock itself. The possibility that there may be two types of acceleration process superimposed on each other, one associated with shock, the other associated with turbulent regions has also been suggested (McDonald et al., 1976; Barnes and Simpson, 1976). However, this question as well as the crucial question of the origin of the pre-accelerated particles remains unresolved. To assist in defining the possible types of acceleration mechanisms we propose in this report to investigate:

A. The relation between the energetic particle events and the propoerties of the high speed solar wind streams.

B. The form of the energy spectrum of the corotating energetic particle streams and its variation with respect to CIR boundaries and with radial distance.

A. Relation Between the Energetic Particle Events and the Properties of High Speed Solar Wind

Measurements of the corotating energetic particle events obtained from Pioneer 10 and Pioneer 11 at large heliocentric distances (1.5-10 AU) have shown that most of the events observed in 1973 and 1974 exhibit a typical double peak structure (Barnes and Simpson 1976; Pesses et al., 1978). The first peak is closely connected with the forward shock.

Its intensity is often lower than the second peak which is generally associated with the reverse shock (Scholer et al., 1979b). At 1 AU and inside 1 AU, Van Hollebeke et al., 1978 have shown that the corotating particle events have a single peak and are contained inside the high speed solar wind stream just adjacent to the low and high speed stream interaction region. Scholer et al., 1979a have shown similar results for 4 successive solar rotations in 1974. We present here a more extensive study using data at 1 AU from the Goddard Space Flight Center IMP 7 low energy detector for the period November 1973 - August 1974. During that time, two well defined recurring high speed streams originating from North and South coronal holes were observed for some 10 solar rotations (Hundhausen, 1977). A representative sample showing a plot of the >.5 MeV particle intensity together with the bulk velocity of the solar wind and the interplanetary field magnitude (from the NSSDC Interplanetary Medium Data Book, J. King, 1977) as a function of time is presented in Figure 1 for four solar rotations. The association between corotating energetic particle increases and the high speed solar wind stream and the magnetic field enhancement produced by the interaction between low and high speed streams is well evidenced in this figure. A striking feature (Figure 1) is the similarity in the time profile of the solar wind velocity and the associated energetic particle increase during the rising part of the event. To show this correlation, the $\sim$1.5 MeV proton intensity is plotted (Fig. 2) versus the solar wind velocity for each of the 16 corotating events observed between Nov. 1973 and Aug. 1974. Each data point represents a 6 hour average and the association is made from the first point which shows a significant increase either in the solar wind speed or the corotating particle intensity up to the maximum intensity of either the solar wind or the particle intensity (whichever occurs last). In order to avoid a too large dispersion and to be able to see any trend of association for individual events as well as the average trend, the different events have been divided into 3 groups depending on their minimum and their maximum intensity. Panel A includes small events with $I_{min} < 2.5\times10^{-3}$ and $I_{max} < 6\times10^{-2}$ particles/cm^2-sec-sr-MV; panel B includes medium size events with $10^{-3} \leq I_{min} < 5\times10^{-3}$ and $I_{max} < 5\times10^{-1}$ particles/cm^2-sec-sr-MV and panel C contains events for which $I_{min} < 5\times10^{-3}$ particles/cm^{2}sec-sr-MV. Figure 2 shows a good correlation between particle intensity and solar wind velocity of the form: $I \propto e^{Vsw/Vo}$ where I is the particle intensity at a given energy and Vsw is the solar wind velocity. Vo varies from event to event from 65km/s to 135km/s with a typical value of Vo = 80km/s during the period under consideration.

From this relation it is possible to make several remarks regarding the distinction between shock acceleration and acceleration due to turbulence in the solar wind. In the first hypothesis, the acceleration is essentially produced between 2 to 4 AU where strong shock pairs are known to develop. The particle stream observed at 1 AU would be the result of the shock accelerated particles. However it should be pointed out that only the decay of the particle event observed at 1 AU can possibly be connected to the particle increase observed in front of the reverse shock at several AU's. The onset portion of the particle increase could then be the result of the inward diffusion of either particles accelerated at the shock which then traverse the shock into the interaction region or else the particle are accelerated in a region closer to 1 AU where weak shocks may form. The striking correlation between solar wind speed and the magnitude of the particle increases rules out the first alternative and may favor the second one if a correlation can be established between shock strength and solar wind velocity.

In the second hypothesis where acceleration is mainly produced by fluctuations in the solar wind, it is possible that associated with the rise time of the observed high speed solar wind stream there are produced wave-particle interaction which are correlated with the solar wind bulk velocity and which might accelerated particles. A preliminary analysis of the power spectrum of the density of the solar wind presented by D. Intrilligator (this conference) may support such association. This needs to be further confirmed.

B. Energy Spectra of Corotating Energetic Particle Events

It has been previously shown (Trainor et al., 1976; Van Hollebeke et al., 1978b)that the energy spectra from 0.5-20 MeV averaged over the 24 hr period of peak intensity were well represented by an exponential in momentum of the form $dJ/dP = C \exp(-P/Po)$ where P is the particle momentum. For these events Po was found to be generally between 12 and 16 MeV/c (Fig. 3). A similar representation was also found for the alpha particles with Po being equal or some 10% smaller. This spectral representation is found to apply from 0.45 to beyond 5 AU. Furthermore the spectral index obtained at event maxima was essentially the same for a given event between 0.45 and 3.8 AU. Extending this study to the events of the Nov. 1973 - August 1974 period using data from the Goddard IMP 7 experiment at 1 AU and the Goddard-University of New Hampshire experiment on Pioneer 11 between ∿3 and 4 AU further confirms the correctness of the exponential in momentum representation. However, for a few very large events at 1 AU there is a spectral flattening below some 60 MeV/c corresponding to protons of ∿2 MeV. This effect is generally seen in association with solar wind bulk velocities greater than 750 km/sec. For this series of events, the presence of a double peak structure in the time-intensity profile observed by Pioneer 11 in association with the forward and reverse shocks (which was not seen in the 1976 corotating particle events) complicates the comparison of particle spectra at different radial distances. Between 3 and 4 AU the spectra display large changes at the time of shock passage while at 1 AU only a single peak is observed as previously noted. Furthermore, the transit time of the solar wind plasma from 1 to 3.5 AU is on the order of 7-10 days which introduces significant time variations. To overcome these difficulties, a method of superposed epoch analysis is introduced in which at each radial distance the time is defined in terms of the azimuthal distance from the interaction region. Po(t) is normalized by Po(t_o) where Po(t_o) is the spectral index at the time the edge of interaction region crosses the spacecraft and Po(t) is obtained from 6 hour averages. At 1 AU the crossing time of the CIR is taken as the onset of the high speed stream. Between 3 and 4 AU the shock crossings have been defined by the magnetic field and plasma observations (E. J. Smith, B. Tsurutani, private communication). The results of this analysis are presented in Fig. 4. At 1 AU the spectrum remains constant during the first two days and then progressively flattens at a rate of ∿0.5% per degree away from the interaction region. Between 3 and 4 AU there are striking differences between the spectral changes observed near the forward and reverse shocks. At the passage of the forward shock the spectrum is the steepest as shown previously for the .54 - 1.84 MeV protons by Barnes and Simpson, 1976, and becomes increasingly harder by some 1% per degree away from the forward shock front. Inside the interaction region the spectrum fluctuates but becomes progressively harder near the reverse shock. Beyond the reverse shock, Po increases slightly.

The distribution of Po measured in the forward, reverse and interaction regions between 3 and 4 AU as well as the 1 AU distributions are shown in Fig. 5. Po is determined from 6 hr averages and the number of events for each distribution has been normalized to 100. Between 3 and 4 AU the energy spectra of the cosmic rays intensity seems to show a wider distribution of Po in front of the reverse shock than in front of the forward shock. The average Po is 10.5 MeV/c in front of the reverse sh ck compared to ∿10 for the particles in front of the forward shock. The particle inside the interaction regions shows a much narrower Po distribution with an average Po of 9 MeV/c. At 1 AU, the spectrum shows a wide distribution of Po from 8 MeV/c to ∿20 MeV/c during this period with an average value of 12 MeV/c. The dominant role of the corotating interaction region as originally proposed by Barnes and Simpson (1976) is clearly confirmed by this study. The spectral changes between ∿.35 and 10 AU appear to be significantly smaller than would be expected from diffusion processes. The observed time histories, radial gradient and spectral distribution now provide an excellent description of these energetic particle events from 0.5 to 10 AU. Clearly the next step is modeling the shock acceleration process combined with interplanetary diffusion. Such a procedure should establish whether or not additional acceleration processes are required. The 1 AU observations during the initial phase of the events suggest other acceleration processes may be necessary.

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Figure Captions

Figure 1 Association between energetic particle streams observed at 1 AU and the high speed solar wind stream shown for 4 solar rotations. The hatched area are flare accelerated particle events.

Figure 2 Correlation between energetic particle intensity and the solar wind bulk velocity during the onset of each of 16 corotating streams observed from Nov. 1973 - Aug. 1974.

Figure 3 Energy spectra of a corotating energetic particle stream observed for 3 consecutive solar rotations in 1976.

Figure 4 Variation of Po with respect to the interaction region.

Figure 5 Distribution of Po measured at different radial distances.

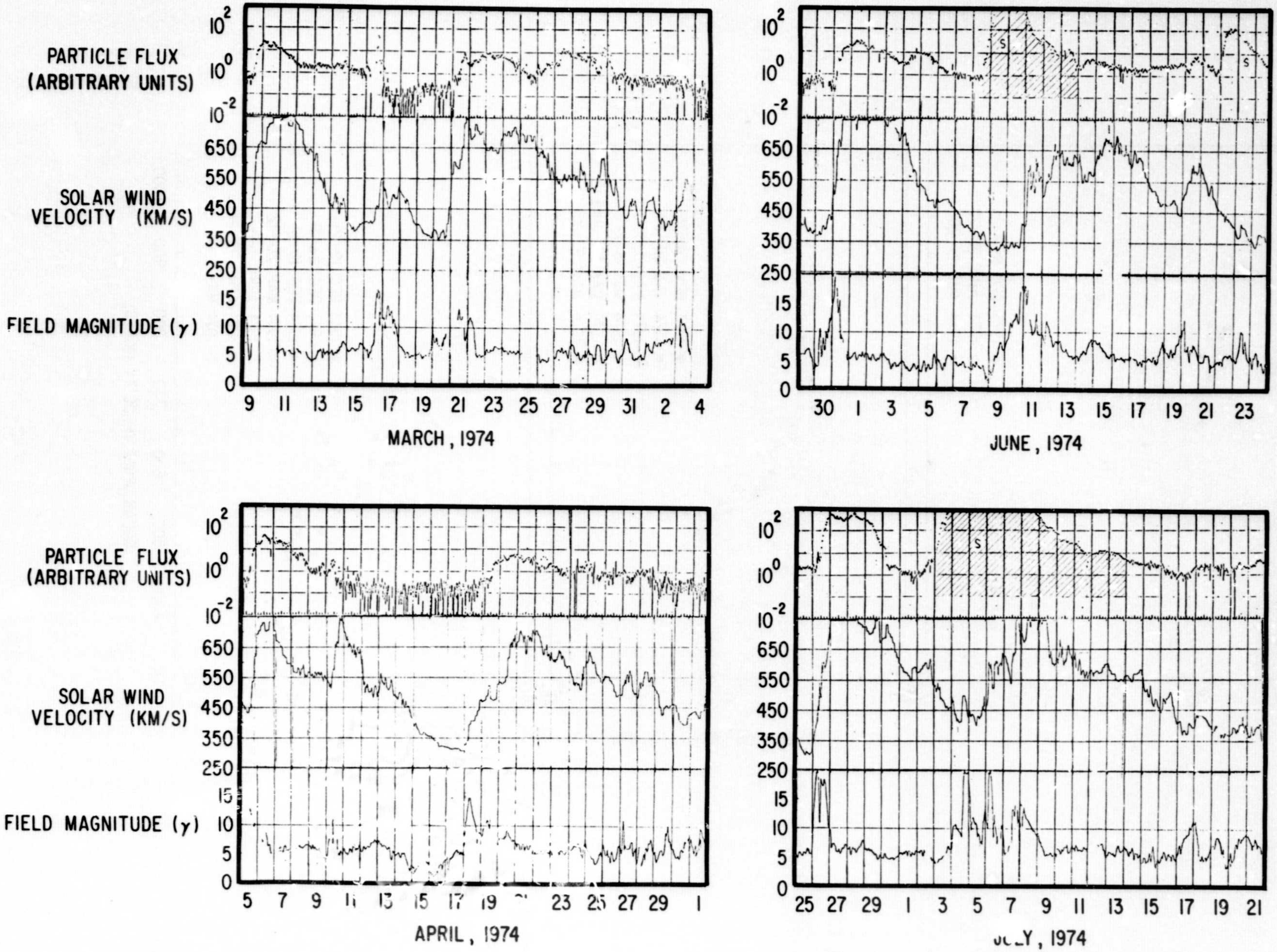
PARTICLE FLUX
(ARBITRARY UNITS)
SOLAR WIND
VELOCITY (KM/S)
FIELD MAGNITUDE (γ)
MARCH, 1974
JUNE, 1974
APRIL, 1974
JULY, 1974

Fig. 1

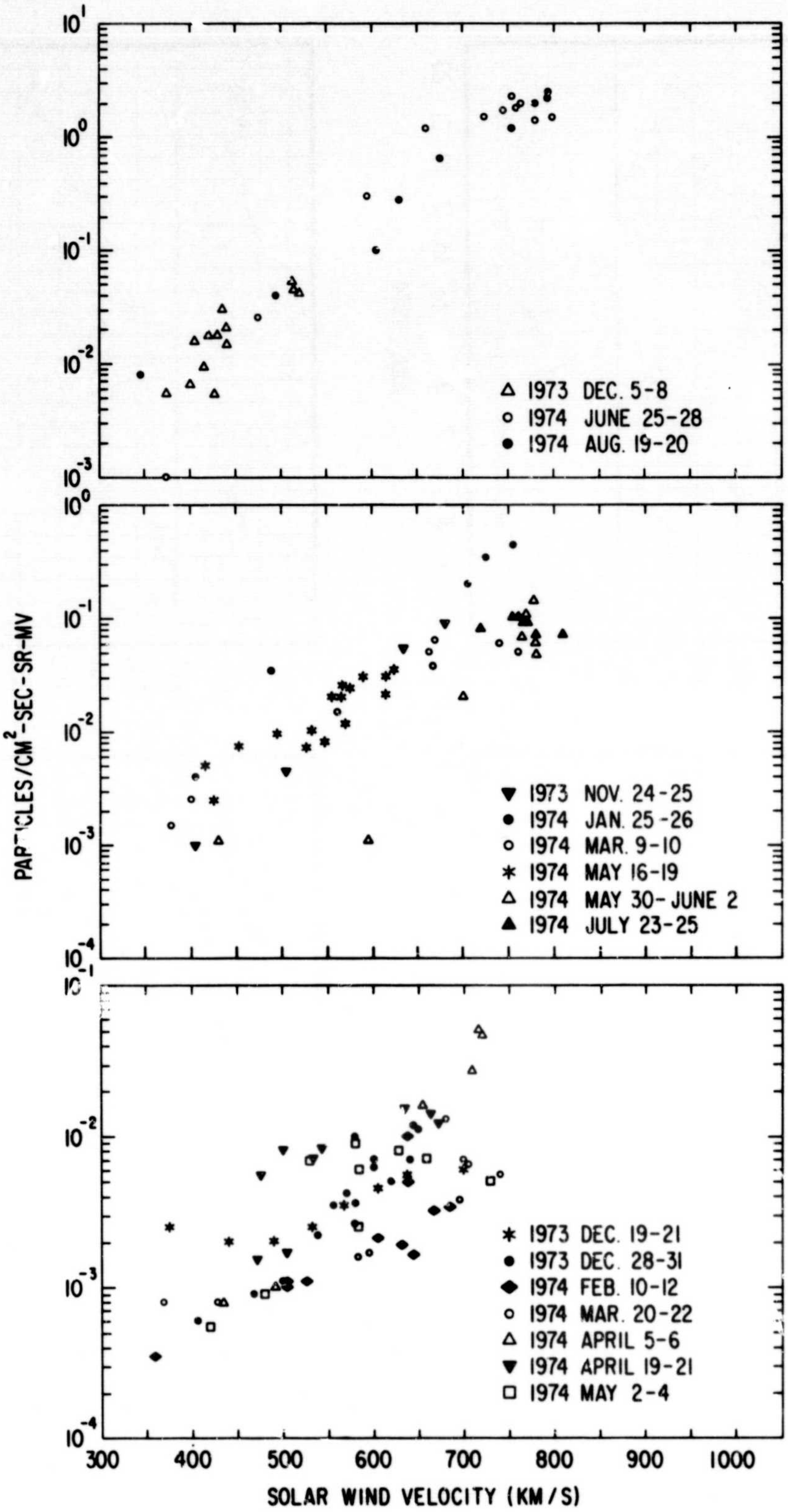
1973 DEC. 5-8
1974 JUNE 25-28
1974 AUG. 19-20
1973 NOV. 24-25
1974 JAN. 25-26
1974 MAR. 9-10
1974 MAY 16-19
1974 MAY 30-JUNE 2
1974 JULY 23-25
1973 DEC. 19-21
1973 DEC. 28-31
1974 FEB. 10-12
1974 MAR. 20-22
1974 APRIL 5-6
1974 APRIL 19-21
1974 MAY 2-4
SOLAR WIND VELOCITY (KM/S)

Fig. 2

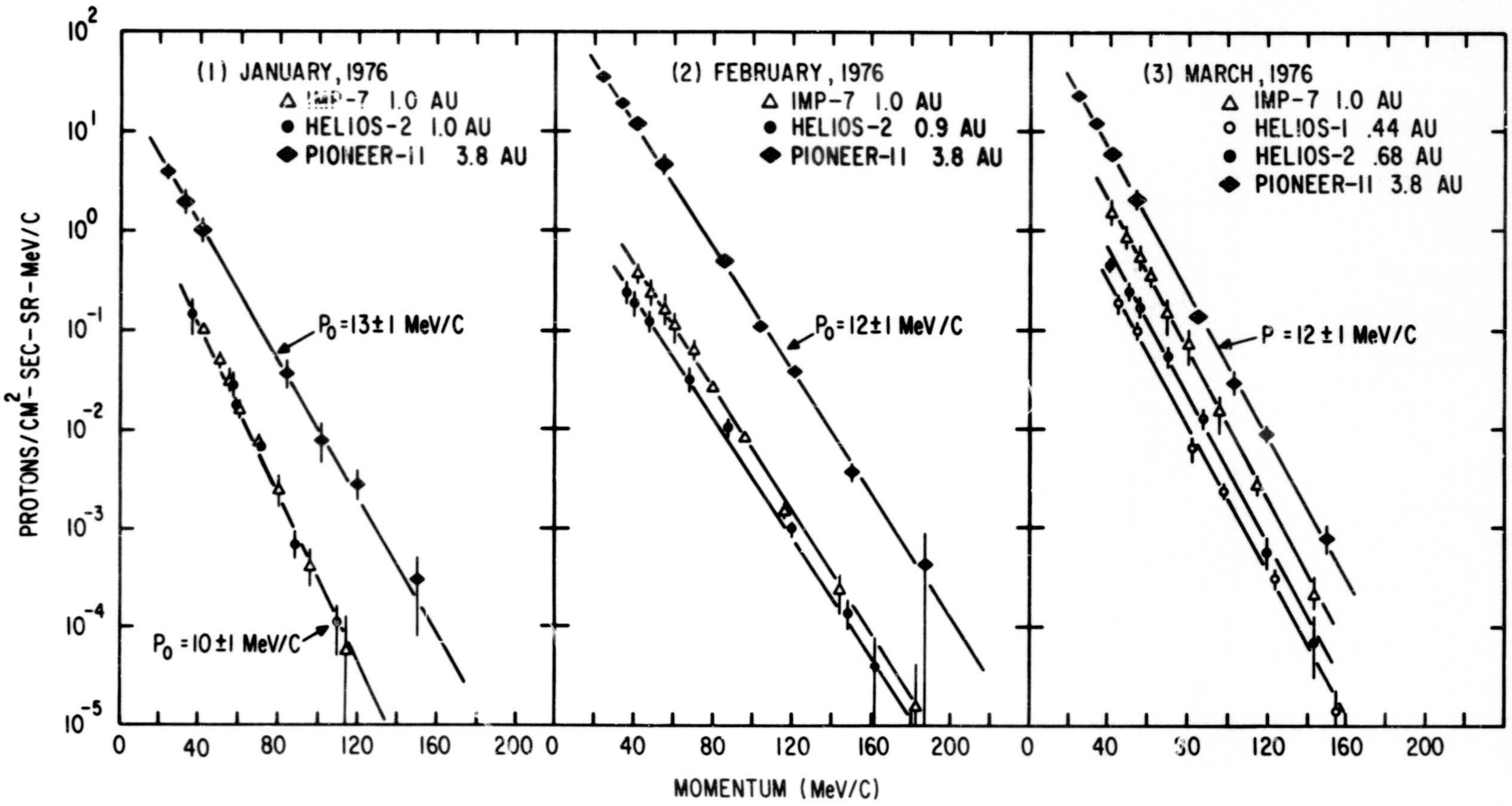
(1) JANUARY, 1976
IMP-7 1.0 AU
HELIOS-2 1.0 AU
PIONEER-11 3.8 AU
P_0 = 13 ± 1 MeV/C
P_0 = 10 ± 1 MeV/C
(2) FEBRUARY, 1976
IMP-7 1.0 AU
HELIOS-2 0.9 AU
PIONEER-11 3.8 AU
P_0 = 12 ± 1 MeV/C
(3) MARCH, 1976
IMP-7 1.0 AU
HELIOS-1 .44 AU
HELIOS-2 .68 AU
PIONEER-11 3.8 AU
P = 12 ± 1 MeV/C
PROTONS/CM^2-SEC-SR-MeV/C
MOMENTUM (MeV/C)

Fig. 3

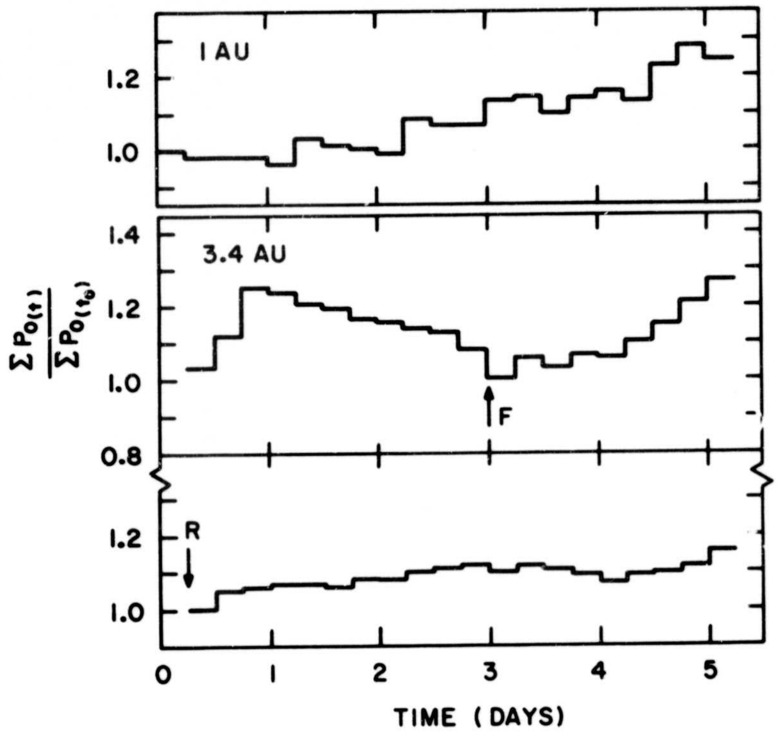

Fig. 4

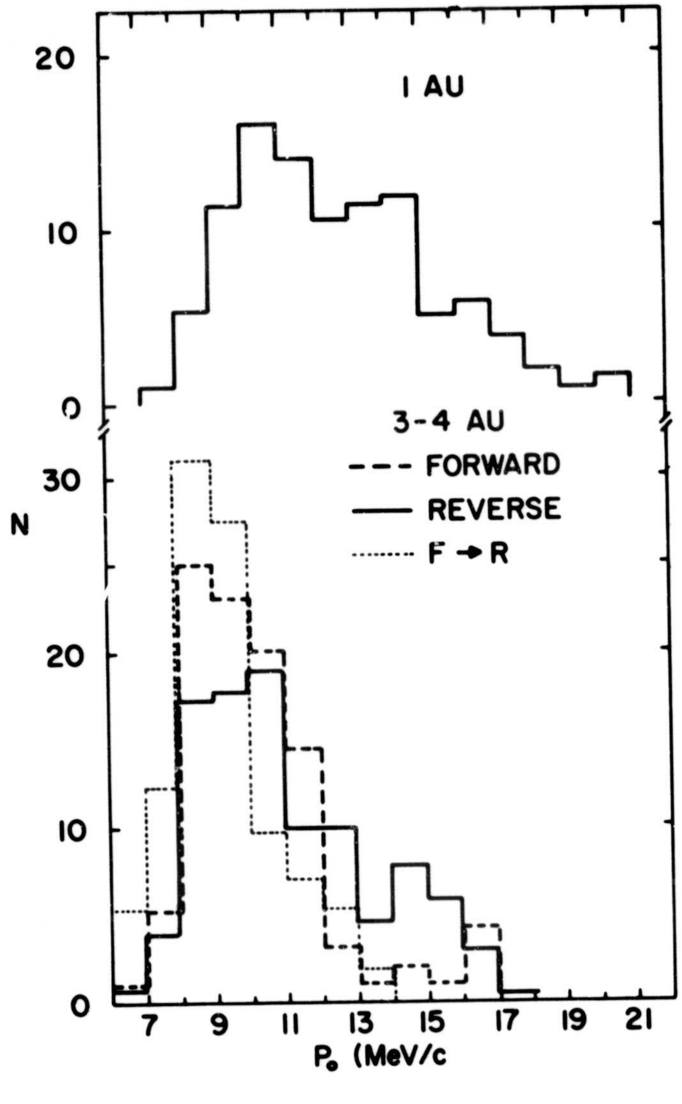
20
I AU
10
0
3-4 AU
FORWARD
REVERSE
F → R
30
N
20
10
0
7
9
11
13
15
17
19
21
P₀ (MeV/c)

Fig. 5