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ABSTRACT

The radial gradient of long-lived, corotating energetic particle streams is measured using observations of .9-2.2 MeV protons from Helios 1 and 2 between .3 AU and 1 AU, IMP 7 at 1 AU, Pioneer 11 at 3.8 AU and Pioneer 10 between 9 AU and 10 AU. These studies cover several time periods from mid-1973 to mid-1976. A positive gradient of ∿350% per AU is found between .3 AU and 1 AU. Between 1 AU and some 3-5 AU, the gradient is variable with an average value of 100% per AU which is consistent with the earlier statistical results obtained from the IMP 7 and Pioneer 11 data. A comparison between measurements at 9 AU and ∿4 AU shows a negative gradient which is variable from -40 to -100% per AU. Possible solar latitudinal effects on these gradient studies are also discussed. Using solar wind and magnetic field data from Helios 1 between 1 AU and .3 AU, the relation between corotating energetic particle events in the inner solar system and the interplanetary medium is examined. It is found that the energetic particles are contained inside the high speed solar wind stream in a region adjacent to the interaction region between low speed and high speed streams.

1. INTRODUCTION

Long lived streams of low energy nucleons ($\sim$0.1-5 MeV) are the dominant type of energetic particle events observed at 1 AU near the time of minimum solar activity. First observed by Bryant et al., 1965, these events are distinguished from flare-associated events by their time profiles, which have a slow rise to maximum intensity and no velocity dispersion during the onset phase, and by the lack of direct association with either optical flares, radio or x-ray emission. These events are corotating with the interplanetary medium and are associated with increased interplanetary magnetic activity, with changes in the interplanetary medium and with decreases in the galactic cosmic ray intensity. They typically last for 4-10 days suggesting a convective region with an angular width of 50^{o}-130^{o}. Studies in this area include Bryant et al., 1965; Fan et al., 1966; Lin and Anderson 1967; Fan et al., 1968; Anderson 1969; McDonald and Desai 1971; Krimigis et al., 1971. All of these studies were interpreted in terms of energetic particles corotating with the Sun which originate from either continuous or impulsive acceleration in a solar active region.

Recently, a series of observations has contradicted this explanation. With the former model, it was expected that, at a given energy, the intensity of these corotating streams convected by the solar wind would decrease rapidly with radial distance due to spatial effects and adiabatic energy loss processes (Gleeson, Krimigis and Axford, 1971; Gleeson 1971). Instead. McDonald et al., 1976, found that the average size of such events between 1 and 4 AU either remains constant or increases by more than one order of magnitude. These authors suggest that interplanetary acceleration processes are the most plausible explanation. They also raise the possibility that some corotating particle increases originate from the suprathermal distribution in the solar wind and are not accelerated at the Sun. Previously, using the data from Zond 3 and Venus 2 between 1 AU and .7 AU and during 1965-1966, Vernov et al., (1970) also found a positive gradient of greater than 200 per cent per AU for some 1.5 MeV proton increases associated with Forbush decreases. Similarily, Roelof and Krimigis, 1973 observed some events with positive gradients using Explorer 35 and Mariner 5. Vernov et al., 1970 also raised the possibility of the acceleration of MeV protons in the inhomogeneties of the solar wind. More recently, Barnes and Simpson, 1976 using Pioneer 11 observations have found a strong correlation between corotating particle events and corotating interaction regions (CIR). They concluded that local acceleration is taking place in or near the CIR and its associated shock fronts. Anisotropy studies of the 1.6 MeV proton increases at 1 AU by Marshall and Stone (1977) show a diffusive streaming towards the sun which is consistent with a positive gradient in the particle density.

The crucial question now becomes the nature of this interplanetary acceleration process and the initial source of the energetic particles. Using a network of cosmic ray experiments on Helios 1 and 2, IMP 7, Pioneer 11 and Pioneer 10, we propose in a series of forthcoming papers to investigate in detail the major characteristics of corotating streams of energetic particles in the inner and outer solar system from .3 AU to

10 AU. In this paper, the radial gradient of these events is studied from .3 AU to 10 AU. Subsequent papers will deal with their energy spectra, anisotropies and more detailed intercorrelation studies with magnetic field and plasma. The radial gradient is of special importance in defining the spatial dependence of the acceleration process. Observations of well defined, corotating particle streams from three different time periods are used to study the temporal and spatial variations of those events. Each period covers four or more solar rotations. It is shown that during the period of observation, a positive gradient exists between .3 AU and 1 AU and that this inner solar system gradient is even more pronounced than that observed between 1 AU and 4 AU. At 10 AU the particle intensity is one to two orders of magnitude lower than that observed at 4 AU.

In addition the relation between the corotating events in the inner solar system and the accompanying interplanetary magnetic field and solar wind is also examined. Inside 1 AU the relation to the high speed solar wind streams appears simpler than in the outer heliosphere.

2. OBSERVATIONS

This study covers three seperate time periods:

i. December 1975 - April 1976 for Helios 1, 2, IMP 7 and Pioneer 10 and 11.

ii. December 1974 - March 1975 for Helios 1, IMP 7, and Pioneer 11.

iii. June 1973 - May 1974 for IMP 7 and Pioneer 11.

The first two periods represent the interval from each Helios launch to the time past its first perihelion. The choice of the first two periods was dictated by the availability of good Helios data coverage. It was also required that the periods chosen were not dominated by flare-associated particle events. The studies reported here used two of the three particle detector systems on Pioneers, Helios and IMP.

(i) The LET I detector consisted of 2 100μ dE/dx detectors and a 2mm total E detector followed by an anticoincidence counter. Multi-parameter analysis is used for protons and alphas from 3 to 21 MeV/nucleon. Single parameter analysis is used at lower energies on the front dE/dx element with an 8 level integral analyser. Particle trajectories for the single parameter analysis are defined by a collimator and the effective range is from ∿0.6 - 2.5 MeV. The equivalent IMP 7 LET I detector used a single 150μ dE/dx device.

(ii) The LET II detector consisted of a 50μ dE/dx device mounted directly above a 2 mm E detector which is followed by an anti-coincidence counter. Collimation is provided by a brass collimator. The front 50μ detector is analysed in 8 integral levels. A more complete description of these systems can be found in Trainor et al., 1974. The Pioneer 10, 11 and IMP 7 level settings are very similar for the LET I and LET II integral analysers. On Helios 1 these levels were altered to favor the response for nuclei with $Z > 2$. On Helios 2, the LET I and II integral levels were changed to enhance the low-energy proton response. The Helios 2 LET II telescope is used to study protons between .50 and 2.2 MeV. For

Helios 1, the differential proton measurements below 2.2 MeV are made via threshold levels of the particle stopping in the LET I 100μ front detector. As will be discussed in the paper on energy spectra, the alpha particle contribution in the single parameter analysis is not important. In addition the electron contribution to both systems is completely negligible. This result has been confirmed by the Pioneer 10 and 11 encounter studies at Jupiter.

The trajectories of the three spacecraft, together with that of Pioneer 10 in the ecliptic plane, are shown in Figure 1a. Helios 1 trajectory (not shown here) is similar to that of Helios 2 except that the line of apsides is displaced to the east by 35°. The heliolatitudes of all spacecraft during the periods relevant to this study are shown in Figure 1b.

a) Period 1: December 1975 - April 1976

Figure 2 shows the time history of the .96 MeV to 2.2 MeV protons detected by IMP 7 at 1 AU, Helios 2 between 1 AU and .3 AU and Pioneer 11 at 3.8 AU for five solar rotations for period 1 extending from December 18, 1975 thru April 30, 1976. The observations (Fig. 2) at IMP 7, near Earth, of a 26 ± 1 day recurrent particle increase numbered "0" thru "4", clearly demonstrate the corotating nature of one long-lived energetic particle stream during this time period. the temporal evolution of this particle stream can be followed from December 28, 1975 thru April 16, 1976 at 1 AU and at 3.8 AU, with event "4" not observed at Pioneer 11 (this observation is complicated by the incomplete data coverage). Helios 2, launched in mid-January 1976, detects the corotating stream within -2 days and +3 days of the IMP 7 observations depending on their relative positions. The corotation time (calculated from a 500 km/s solar wind velocity) is in good agreement with the observed delay between particle increases observed at Helios, IMP 7 and Pioneer 11. For example the delays between events observed at IMP 7 and at Pioneer 11 from event "0" to event "3" are respectively 5, 6, 3, 1.5 days, compared to calculated estimates of 6, 5, 3, 2. The IMP 7 and Helios 2 trajectories are both in the ecliptic plane. Their heliolatitudes vary from -5° to -7° and are approximately the same from the launch of Helios 2 on January 18 to the end of March. However, due to its solar elliptical orbit with a 6 month periodicity, Helios 2 rapidly changes heliolatitude from -7° on March 22 to 0° near perihelion on April 12 and to $+7^{\circ}$ on April 22. Pioneer 11 is at a heliolatitude of $\sim+15^{\circ}$. Note that the relative heliolatitudes of Pioneer 11 and IMP 7 are almost constant from February thru April 1976. The intensity vs. time profile of the corotating events detected at those 3 positions is changing from one rotation to the next. At 1 AU, the maximum intensity of the corotating-event first decreases between December and January, then increases during the next two solar rotations and decreases abruptly in April after the series of flare associated events at the end of March 1976. At 3.8 AU, the same general temporal trend is observed by Pioneer 11. The maximum intensity of the events observed at Pioneer 11 is a factor two to twenty bigger than the corresponding ones at 1 AU as was statistically observed for parts of the third time period by McDonald et al., 1976. However, in April, there appears to be evidence for a smaller flux at Pioneer 11. There is complete agreement in the data of Figure 2 between the measured intensities of Helios 2 and IMP 7 at 1 AU. As Helios 2 moves closer to the Sun, the corotating events become smaller than that observed at approximately the same time by IMP 7 at 1 AU. The relative intensity between IMP and Helios is apparently independent of the temporal evolution of the corotating stream. For example, the amplitude of the corotating event seen at 1 AU increases between February 18 and March 16 while it stays constant or decreases during the same time period as seen by Helios 2 moving from .92 AU to .66 AU.

During event "4", in April, (Fig. 2) Helios 2 is at .3 AU from the Sun. Because of the satellite trajectory and its speed, relative to a fixed solar heliolongitude, the duration observed by Helios 2 is about twice as long as that measured at IMP-7. Otherwise the event duration does not change significantly with radial distance; for most of the increases this duration is $\sim$5 days during this period of 5 solar rotations. However, occasional small increases of intensity at the leading or the trailing edge of the main portion of the increase may change with radial distances. The abruptness of the decrease of the intensity in the tail of the event detected by Pioneer 11 is essentially due to the larger signal to background ratio. These is a significant similarity in the time profile of the events observed at different radial distances whenever the co-rotation time lag is not too large. This suggests that particles diffuse very little across the interplanetary magnetic field lines.

At $\sim$10 AU these events, as detected by Pioneer 10 (Fig. 3), are not as well defined as they were at $\sim$4 AU. In particular, they last longer and often appear as broad double peaks. However, there seems to be no doubt of the association between the two sets of observations. The dates of the maximum intensities seen at Pioneer 10 are respectively: event "0", January 20; event "1", February 11; event "2", March 10; event "3", April 3. Those times are in relatively good agreement with the predicted values computed from a 500 km/s solar wind velocity which are respectively: January 16, February 10, March 7 and April 2. The event "4" which should have occured around April 26, did not have any appreciable increase above the background flux, in agreement with observations at $\sim$4 AU.

b) Period 2: December 1974 - April 1975

The time history of the $\sim$1 MeV proton intensity detected by IMP 7 at 1 AU and Pioneer 11 between 5 AU and 4.5 AU is shown in Figure 4 for period 2 which extended from December 9, 1974 thru April 10, 1975. The data are organized in a 25 day siderial solar rotation period. In this reference system, each data set is referenced to a fixed heliolongitude at the first day of each 25 day interval. To first order the corotation delay between IMP 7 and Pioneer 11 is computed from the following relation:

$$\Delta\psi_{(P11-I7)} = \psi_{o(P11)} - \psi_{o(I7)} + \frac{\Omega_{\odot}}{V_{sw}} (R_{P11} - R_{I7}) \qquad (1)$$

where $\psi_{o(p11)}$ and $\psi_{o(I7)}$ are respectively the fix heliolongitudes of Pioneer 11 and IMP 7 at the first day of the time interval. R_{P11} and R_{I7} are the respective heliocentric distances of Pioneer 11 and IMP 7, $\Omega_{\odot}$ is the sun siderial rotation in degree/s and V_{sw} is the solar wind velocity expressed in Km/s.

In this expression $\psi_{o(P11)} = 0^o \pm 7^o$, $\psi_{o(I7)} = 80^o$ and $\Omega_{\odot} = 1.66\ 10^{-4}$ degree/s. Although this relation neglects stream-stream interaction, it gives very good agreement for the period 3 events when Pioneer 11 was between $\sim$3 and 4 AU.

According to relation (1),

$\Delta\psi_{(P11-I7)}$ may vary from $\sim 165^o$ to $\sim 40^o$ for a solar wind speed varying from 400 km/s to 800 km/s. Thus, Pioneer 11 is expected to see corotating structure some 11.4 to 2.8 siderial days after IMP 7 depending on the solar wind velocity. If the stream speeds do not vary from rotation to rotation, a constant delay between IMP 7 and Pioneer 11 should be observed in Figure 4 which is the case for periods 1 and 3.

The IMP 7 data show a recurrent particle stream starting on December 18, 1974 (A_1) which can be followed thru the fifth solar rotation with the event A5 on March 30, 1975. Those events present large intensity variations from one rotation to the next with events A2 and A5 being just above the background level (indicated by a dashed line). Flare associated particle events observed at 1 AU are indicated by arrows. The solar flare event identification is based essentially on the requirement for velocity dispersion in the case of low energy particle events (<20 MeV). At higher energy, additional information such as optical flare, radio burst, and electron association generally leave little ambiguity. Note that no corotating event with a flux of $>10^{-4}$ particles/cm^2-sec-sr-MeV has been found at energies above 20 MeV. During the first and second solar rotations, flare associated particle events tend to obscure the time history of the corotating structures. However, it is clear that for each solar rotation after the first one, only a single significant recurrent structure is observed by IMP 7 (Series A). On the first rotation, an additional increase (B1) is seen in association with the narrow solar wind stream originating from a North coronal hole extending to the solar equator as it will be later discussed. Recurrence of the corotating particle stream (B1) are observed at energies less than 500 keV with an intensity less than $5x10^{-2}$ particle/s-cm^2-sr-MeV. The main increase of the series (A) events above $2x10^{-1}$ particle/s-cm^2sr-MeV lasts less than 5 days.

At Pioneer 11, a corotating stream (D) is particularly evident from rotation 2 to rotation 5. Due to the proximity of Jupiter in December, there may be some jovian effect during the early part of the first solar rotation. The Jovian increases near Jupiter are $\leq$ 1 day in duration. The interplanetary increase above .2 particle/s-cm^2-sr-MeV lasts about ten days. Similar features can be recognized in the intensity profile from one rotation to the next with some variability in the intensity. The second rotation shows an increase before the main one which does not seem to reoccur with any significant amplitude the following rotation. The observed corotating delay of ~6 siderial days (which corresponds to V_{sw} ~550 km/s) between this increase and B1 at IMP 7 makes this increase a possible candidate as a (B) associated corotating stream. There is no obvious association at 5 AU with the corotating particle stream (A) observed at 1 AU.

Without any correlation with plasma data at 5 AU, it is not clear if the corotating particle stream (D) observed at 5 AU represents the sole association with the stream (B) or if it is the product of an eventual interaction between stream (A) and stream (B) at 5 AU. Since Pioneer 11 and IMP 7 were at different heliolatitudes (Figure 1b), a possible latitudinal effect will be examined in the next section.

Inside 1 AU, observations of the corotating events detected by Helios 1 moving from 1 AU in December 1974 to perihelion at ~.3 AU on March 16, 1975 are depicted in Figures 7 and 8 with reference to a fixed heliolongitude. Corotating particle streams are indicated by a bracket and solar flare associated particle events are indicated by arrows. The origin of one low energy event on February 21 has not been established. As in the case of the observations at IMP 7 (Figure 4), a recurrent particle stream (A) can be followed during four solar rotations. (The lack of a fifth rotation at Helios 1 is due to the absence of data coverage during this time interval). The time history of the ~1 MeV proton intensity from December 16, 1974 to February 8, 1975 is nearly identical at both IMP 7 (Figure 4) and Helios 1 (Figure 7) with the event (B1) seen on the first rotation only. In February, the time profile of the event (A3) detected by Helios 1 at .66 AU is similar to the corresponding one detected by IMP 7 at 1 AU except that the amplitude is smaller at Helios 1. the time history of the event (A4) as detected by Helios 1 during its perihelion at ∿.3 AU is complicated by the superposition of the solar flare associated particle events on March 17, 19 and 20. The maximum intensity of this corotating stream is more than one order of magnitude smaller than the corresponding one at IMP 7. In addition to the stream (A), a particle increase labelled (C) does not have any corresponding increase at IMP 7. This case will be discussed in a later section.

c) Period 3: June 1973 - June 1974

In this section a more complete analysis has been performed on the corotating events previously reported from Pioneer 11 and IMP 7 from June 1973 thru June 1974 (McDonald et al., 1976). During Pioneer 11's voyage from 1 AU to 2.6 AU (April 1973 - November 1973) the superposition of solar flare associated particle events and corotating events makes it difficult to differentiate between the two types of events. In June 1973, and from November 1973 thru June 1974, when only a few flare associated particle events were observed, a corotation time calculated from an average 500 km/s solar wind velocity, (in agreement with solar wind observations from 1973 thru December 1975; Gosling et al., 1977) has been used to associate individual events observed at 1 AU with those observed at ~1.3 AU and between 2.6 AU and 5 AU. Within ± 1.5 days, there was good agreement between the calculated and the observed delay except in two cases where the observed delays were 2 and 2.5 days longer than the calculated ones. However, during this period 3, some events detected by Pioneer 11 showed a different intensity profile than their associated ones at 1 AU. In particular, the formation of doubled-peaked maximum structure are observed at Pioneer 11 for some events (McDonald et al., 1976, Barnes and Simpson, 1976). In those cases, it was not clear which of the two peaks should be associated with the 1 AU events. However, the persistance of two recurrent particle streams detected at both IMP 7 and Pioneer 11 from mid-1973 thru 1975 and their association at 1 AU with two recurrent long-lived high speed solar wind streams made the association between the observation at IMP 7 and at Pioneer 11 highly reliable.

In summary, for periods 1 and 3, it was possible to find co-rotating events at Pioneer 11 between 1.6 and 5 AU corresponding to events observed at 1 AU with a corotation delay within ± 1.5 days of the value computed from a 500 km/sec solar wind velocity. Such an association was also possible with Helios 1 and 2 whenever data were available. Pioneer 10 observations were considered only during the first period (December 1975 - April 1976) and were in reasonable agreement with the calculated co rotation delay. However the events in period 2 beyond 1 AU did not display this good agreement and so they were not used in the following analysis.

3. RADIAL GRADIENT

In order to examine the variation of the maximum amplitude of the corotating events with radial distance, the Pioneer 10 and 11, Helios 1 and 2, .9 to 2.2 MeV proton maximum intensity relative to that observed at 1 AU by IMP 7 is plotted in Figure 5 as a function of radial distance for the different periods previously discussed. The events labelled "0" thru "4" are those of Figures 2 and 3. In early 1976, the data coverage on Helios 1 was complete only during events "3" and "4". As discussed earlier, the period 2 included only four points between .3 AU and 1 AU. They are the intensity ratios between Helios 1 and IMP 7 for the corotating events (A1), (B1), (A3), (A4) observed early in 1975 and shown previously in Figure 4 for IMP 7 and Figures 7 and 8 for Helios 1. Event (A2) has not been included because of the poor definition of this event at both spacecraft due to the small intensity to background ratios. The fifth solar rotation with event (A5) is missing at Helios 1 due to lack of data coverage. The event labelled (C) at Helios 1 is not included because it is not observed at 1 AU. This event will be discussed in a later section.

Period 3 includes corotating events detected at both IMP 7 and Pioneer 11 from June 1973 thru June 1974 (McDonald et al., 1976). The diamonds and stars refer to the two different corotating streams which develop during this time period. As noted previously, some events detected by Pioneer 11 during this time period showed a different time profile than their associated ones at 1 AU, making difficult the comparison of maximum intensity detected at the two spacecraft positions. In such cases, the intensities relative to 1 AU were made at both peaks and are shown in Figure 5 as two connected individual points.

Based on the observations presented in Figure 5, it is clear that, at a given energy, there is a positive gradient between .3 AU and 3.8 AU which varies from event to event. The average value is 350 ± 150% per AU between .3 AU and 1 AU. Between 1 AU and 4 AU, the gradient is somewhat smaller. Based on these data it ranges from 20 to 200% per AU. Between 4 AU and 10 AU, the observed gradient becomes negative and varies between -40% and -100% per AU for the events of period 1.

Near 5 AU or beyond 5 AU, events detected at Pioneer 10 were reported to be smaller than those observed by Pioneer 11 close to 4 AU (McDonald et al., 1976).

Despite the significant dispersion of points, between 2.6 AU and 5 AU and between 9 AU and 10 AU, the large number of observations assembled in Figure 5 strongly supports the evidence of a positive gradient between .3 AU and 3-4 AU and a negative one between some 3-4 AU and 10 AU. The change from positive gradient to negative one is very likely taking place in a region between 4-6 AU.

4. LATITUDINAL GRADIENTS

It is expected that these corotating particle events should vanish at the solar poles and hence should display large scale variations in solar latitudes. While the latitude span covered by the 5 spacecraft is relatively small (Figure 1b) it nevertheless is of interest to examine the data for possible evidence of this effect. There are several periods when two or more spacecraft were at the same heliolatitude. This is particularly true for events detected in the inner solar system at Helios 1 and 2 and at IMP 7 during period 1 for events 1, 2 and 3 and for Helios 1 and IMP 7 during period 2 for events A1 and A3. Those points show a definite positive radial gradient between .44 AU and 1 AU. In the outer heliosphere the closest heliolatitude of Pioneer 11 relative to that of IMP 7 is in June 1973, and November 1973, respectively at $\sim -3^{o}$ and $\sim +2^{o}$ at radial distances of ~ 1.5 AU and ~ 2.7 AU. The difference in heliolatitude can be as large as $\sim 22^{o}$ during period 1 in 1976.

Figure 6 shows the relative intensity observed at different radial distances with respect to the observer relative heliolatitude for all the events shown previously in Figure 5. The observer relative heliolatitude is defined with respect to IMP 7 heliolatitude, it is positive when the observer is North of IMP 7 and vice versa.

During period 3, two recurrent high speed solar wind streams were present. One has been associated with a North coronal hole, the other one with a South coronal hole (Hundhausen, 1977). The associated particle streams are represented respectively by stars and diamonds. Other events include those detected during period 1 in 1976 and period 2 in early 1975.

Though Pioneer 11 was between $\sim+3^{o}$ and $\sim+5^{o}$ North heliolatitude during the detection of the North and South coronal hole associated streams, there is no evidence of difference in the relative particle intensity of the associated particle streams. Overall, data at Helios and at Pioneer 10 and 11 display a large dispersion and no particular trend with heliolatitude.

However, there were two cases where observations at one spacecraft position could not be matched with those at IMP 7. One of these was the series of recurrent particle streams observed at Pioneer 11 during period 2 and the other was event (C) detected by Helios 1 also during period 2 (Figure 8).

During period 2 (January 1975 to April 1975) Pioneer 11 was between heliolatitude $\sim+7^{o}$N and $\sim+9^{o}$N and IMP 7 was between heliolatitude -2^{o}S and $\sim-7^{o}$S. Similarly Helios 1 was at heliolatitude $\sim+7^{o}$N and IMP 7 at heliolatitude $\sim-6^{o}$S at the time of event (C).

During this time period, there were two solar wind streams with one originating from a North coronal hole and the other from the South coronal hole. The associated high speed solar wind streams were observed at $\sim$1 AU in conjunction with the particle streams. If a latitudinal effect were the explanation for the difference in the IMP 7 and Pioneer 11 or Helios 1 observations, then it would be expected that IMP 7 would observe a <u>weak</u> corotating event in association with the solar wind stream originating from a North coronal hole and a larger particle event in association with the solar wind stream originating from the south coronal hole, with Pioneer 11 observing a large corotating particle stream in connection with the solar wind stream originating from the North coronal hole. Similarly, Helios 1 at heliolatitude $\sim+7^{\circ}$N would observe a particle stream (C) associated with solar wind stream which may have originated from the North pole coronal hole. While such a pattern may be observed for period 2, it cannot be definitely established since it was not possible to correlate the IMP 7 and Pioneer 11 event with the plasma data. However, the remaining data (Figure 6) do not provide any evidence for a correlation between the events size and the observer heliolatitude relative to the associated solar wind stream heliolatitude.

A possible interpretation of this apparent discrepancy is a second order latitudinal effect: Plasma streams are known to vary both in size and in intensity with heliolatitude (see for example Hundhausen, 1977, Schween et al.,1976). In the same way, widely separate streams may merge at variable radial distances depending on their relative width and strength. We feel that it is not possible to speculate on the heliolatitudinal variation alone without further knowledge on the latitudinal and longitudinal variation of the solar wind at variable radial distances. However from the data in Figure 6, it is clear that heliolatitudinal effects, if there is any within -7° to $+15^{\circ}$ of the solar equator, are small in comparison with the radial effect. It is expected that those effects would be related to variation of the plasma stream intensity and/or the strength of interaction with heliolatitude which may be variable from one solar rotation to the next.

5. COROTATION PARTICLE AND FAST PLASMA STREAMS

Beyond 1 AU the high speed solar wind streams steepen and form corotating shocks which are accompanied by increases in the interplanetary magnetic field (Smith and Wolfe, 1976; Gosling, et al., 1976). These have been designated as CIR's (corotating interaction regions). The correlation between high speed streams and corotating particle events was discussed by McDonald, et al., 1976 and studied in detail by Barnes and Simpson (1976) and Pesses et al., 1977. These latter studies found a strong correlation between energetic particle events and CIR's. However the exact physical coupling is still not clear. It is therefore useful to extend this study to the inner solar system.

Here it is found that most of the corotating particle events are contained inside a high speed solar wind stream in the region just adjacent to the interaction region between low speed and high speed streams. The detailed correlation between plasma and magnetic field data is shown in Figures 7 and 8 for the series of corotating events detected during period 2 by Helios 1 moving from 1 AU in December 1974 to perihelion at .3 AU in March 1975. The 6 hour average $\sim$1 MeV proton intensity is plotted with reference to a fixed heliolongitude, together with the plasma velocity measured aboard Helios 1 (Rosenbauer et al., 1977) and the magnetic field intensity observed aboard the same spacecraft by Burlaga et al., 1976. The flare associated particle events are indicated by arrows and corotating particle streams are indicated by brackets. During this time period the origin of one low energy event on February 21 has not been established.

There were two well-pronounced long-lived fast-speed solar-wind streams which started many solar rotations earlier from the end of 1973 and persisted with little change through 1974 and 1975 (Bame et al., 1976). The broad one (labelled A) has been associated with a South pole coronal hole which extends to the solar equator near Carrington longitude 120° while the narrow solar wind stream (B) was associated with a North pole coronal hole extending to or beyond the solar equator near Carrington longitude 270°, (Schwenn et al., 1976). At the leading edge of those solar wind streams were well defined increases in the interplanetary magnetic field which peak during the rising part of the solar wind increase. At 1 AU and inside 1 AU, it is clear that particle enhancement is associated with the leading edge and the inside of the fast plasma stream. The strong magnetic field which coincides with the interaction region between low and high speed wind streams is also evident anytime a particle increase is observed. A preliminary analysis of a larger number of particle corotating streams observed by IMP 7 at 1 AU shows similar correlation. Note however, that these associations appear to be necessary conditions for the particle enhancement but are, by no means, sufficient as the lack of significant particle increase association with the stream (B) from the second solar rotation in Figures 7 and 8 seem to indicate.

6. CONCLUSION

Based on the study of the variation with distance of several long lived corotating particle streams, new evidence for a positive gradient between .3 AU and some 3-4 AU and a negative one beyond some 3-5 AU has been presented in this paper. The consistency between temporal variations measured at three different radial distances during 5 successive solar rotations during period 1 in addition to the short time lag between measurements at different radial distances, rule out the possibility of a temporal effect in explaining the observed gradient. Extensive comparison of the relative amplitude of the particle stream with heliolatitude also rules out the possibility of a first order latitudinal effect in interpreting the observed gradient.

In conclusion, independently of possible secondary latitudinal effects, it has been shown that between .3 AU and 1 AU, in a region where gradients up to 300% per AU exist, the particle stream is propagating inside a fast solar wind stream in a region adjacent to low and high speed stream interactions. Inside 1 AU, stream-stream interactions are known to exist without shock production (Schwenn et al., 1976). The stream-stream interaction in the solar wind generates large scale fluctuations and beyond 1 AU the interface steepens into corotating forward and reverse shocks. The high speed stream then is a source of both enhanced fluctuation and shock waves. These give rise to a number of possible acceleration processes. Jokipii (1971) and Wibberenz and Beuermann (1971) have proposed that second-order Fermi acceleration by Alfven waves could be important and Fisk (1976) has proposed acceleration by transit-time damping. Shock acceleration has been studied extensively both theoretically and experimentally (e.g.: Shatzmann, 1963; Axford and Reid, 1963; Jokipii, 1966; Sonnerup, 1969; Fisk, 1971; Singer and Montgomery, 1971; Chen and Armstrong, 1975; Levy et al., 1975; Bryant et al., 1962; Rao et al., 1967; Ogilvie and Arens, 1968; Armstrong et al., 1970; Sarris et al., 1975; Ipavich et al., 1975). The relative role of these various mechanisms is not clear at this time. Further study is also necessary to determine if the acceleration occurs in a restricted region of space or along the interaction region from 0.3 AU out to ∿4 AU or beyond. The fact that a negative gradient is observed between 4 and 10 AU probably represents changes in the CIR region with radial distance. This is expected from the decay length of the order of 5-10 AU for a typical long wavelength solar wind speed fluctuation (Hundhausen and Gosling, 1976).

It is not clear at this time whether there is preferential acceleration between 3-6 AU with convective and diffusive transport outside this region. It is established however that the acceleration process is a maximum in this region.

Figure Captions

Figure 1a Trajectories of IMP 7, Helios 2, Pioneer 10 and Pioneer 11 in the ecliptic plane. Helios 1 trajectory is similar to that of Helios 2 except that the line of apsides is displaced to the east by 35^{o}.

Figure 1b Heliolatitude of IMP 7, Helios 1, Helios 2, Pioneer 10 and Pioneer 11 during periods relevant to this study. Dots during those time intervals indicate the position of the spacecraft during the different corotating events observation.

Figure 2 Time history of the .96-2.2 MeV protons detected respectively by IMP 7, Helios 2 and Pioneer 11 during period 1. Brackets indicate the long-lived recurrent corotating energetic particle stream.

Figure 3 Pioneer 10 time history of the ~1 MeV proton intensity during observation of the 1976 corotating events. During this time interval, Pioneer 10 radial distance varies from ~9 AU to ~10 AU at heliolatitude of ~ $+7.5^{o}$N.

Figure 4 Observation of corotating particle streams detected at IMP 7 and Pioneer 11 during Period 2. The data are plotted in a 25 days siderial solar rotation periodicity. In this reference system, each data set refers to a fix heliolongitude during the entire time interval which is that of the first day of the interval. For Pioneer 11, $\psi_{o(P11)} = 0^{o} \pm 7^{o}$ at IMP 7, $\psi_{o(I7)} = 80^{o}$. The IMP 7, Julian dates are indicated on the top of each panel. Corotating streams are indicated by brackets. Brackets labelled A or B refer to corotating events observed by IMP 7, while brackets labelled D are those observed by Pioneer 11. Flare associated particle events observed at IMP 7 are indicated by arrows.

Figure 5 Relative intensity of the .96-2.2 MeV protons versus radial distance. The reference particle intensity is from IMP 7 at 1 AU. Between .3 AU and 1 AU, data are from Helios 1 for the corotating events detected during period 2 and from Helios 1 and 2 for events detected during period 1. At ~ 1.5 AU and between 2.6 AU and 5 AU, data are from Pioneer 11 for the corotating events detected during periods 1 and 3. Between 9 AU and 10 AU, data are from Pioneer 10 for the corotating events detected during period 1. During period 3, two recurrent high speed solar wind streams were present. One has been associated with a North coronal hole, the other one with a South coronal hole. The associated particle streams are represented respectively by stars and diamonds. The event in June 1973 at ~1.5 AU represented by a star has no clear identification.

Figure 6 Relative intensity of corotating events as a function of the observer relative heliolatitude. The relative heliolatitude is with respect to IMP 7 heliolatitude. It is positive when the observer is North of IMP 7 heliolatitude.

Figure 7 Correlation between corotating particle streams, (~ 1 MeV Protons) solar wind velocity and interplanetary magnetic field detected by Helios 1 as the spacecraft moves from 1 AU in December to .7 AU in early February. Data are plotted with respect to a fixed heliolongitude. Brackets indicate corotating particle events, arrows indicate the flare associated particle events. Associations with high speed solar wind streams are good during the first rotation. On the second rotation, the corotating particle events (A2) associated with the broad stream is just above background level of .25 particles/sec-sm^2sr-MeV; no particle events with proton ~ 1 MeV above .25 particle/sec-cm^2sr-MeV is seen in association with the narrow stream.

Figure 8 Correlation between corotating particle streams, solar wind velocity and interplanetary magnetic field detected by Helios 1 as the spacecraft moves from .7 AU in February to perihelion at .31 AU on March 15. Note that changes in the solar wind stream pattern in the last solar rotation is a consequence of the change in heliolatitude which varies from -6.9^{o} on March 3 to 0^{o} on March 15 and $+7.2^{o}$ on April 1. (Schwenn et al., 1976)

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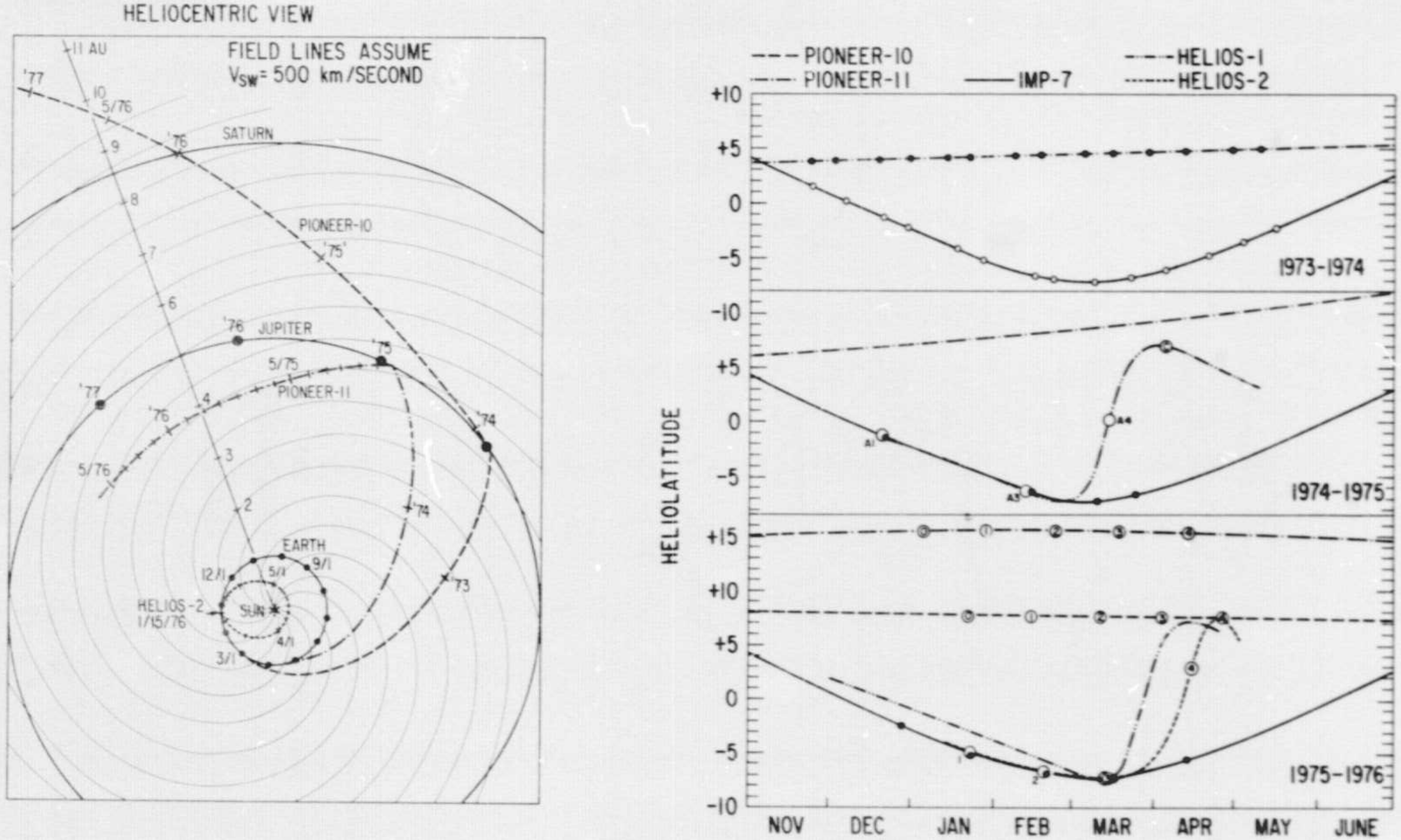
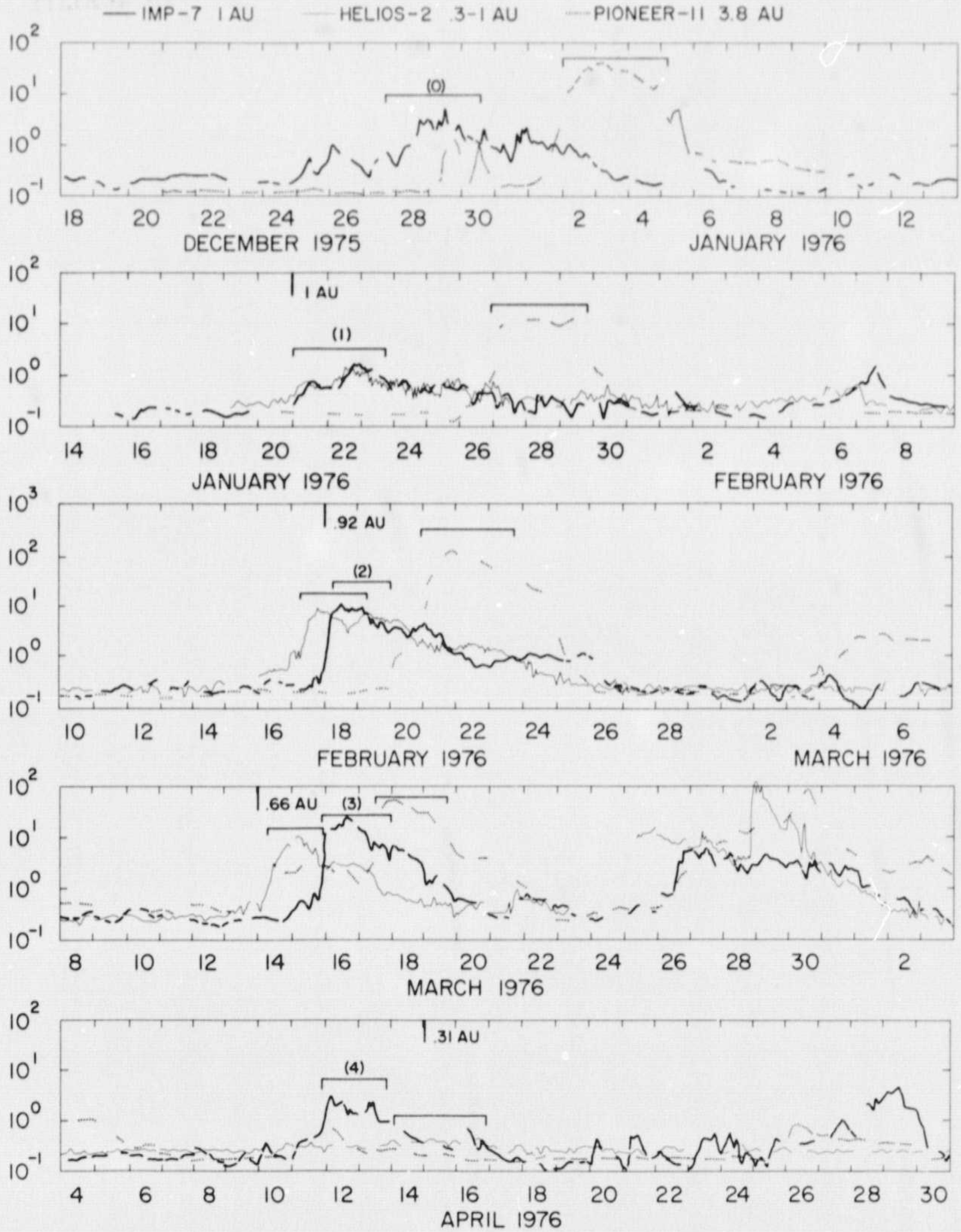

HELIOCENTRIC VIEW
FIELD LINES ASSUME
V_{SW} = 500 km/SECOND
11 AU
SATURN
PIONEER-10
JUPITER
PIONEER-11
EARTH
SUN
HELIOS-2
1/15/76
PIONEER-10
PIONEER-11
IMP-7
HELIOS-1
HELIOS-2
HELIOLATITUDE
1973-1974
1974-1975
1975-1976
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUNE

(a)

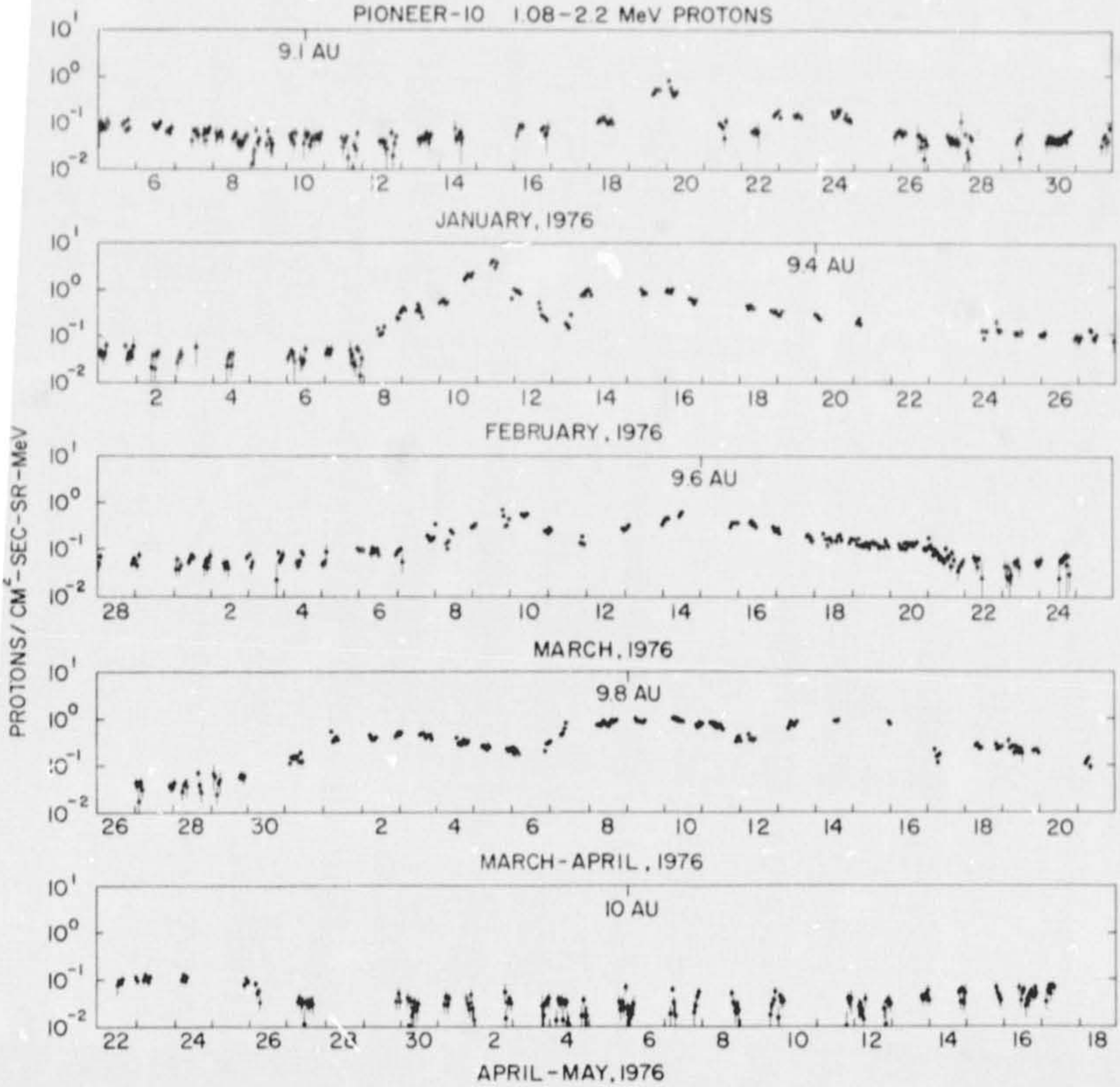
(b)

Fig. 1



IMP-7 1 AU
HELIOS-2 .3-1 AU
PIONEER-11 3.8 AU
(0)
DECEMBER 1975
JANUARY 1976
1 AU
(1)
JANUARY 1976
FEBRUARY 1976
.92 AU
(2)
FEBRUARY 1976
MARCH 1976
.66 AU
(3)
MARCH 1976
.31 AU
(4)
APRIL 1976

Fig. 2



PIONEER-10 1.08-2.2 MeV PROTONS
9.1 AU
JANUARY, 1976
9.4 AU
FEBRUARY, 1976
9.6 AU
MARCH, 1976
9.8 AU
MARCH-APRIL, 1976
10 AU
APRIL-MAY, 1976
PROTONS/ CM²-SEC-SR-MeV

Fig. 3

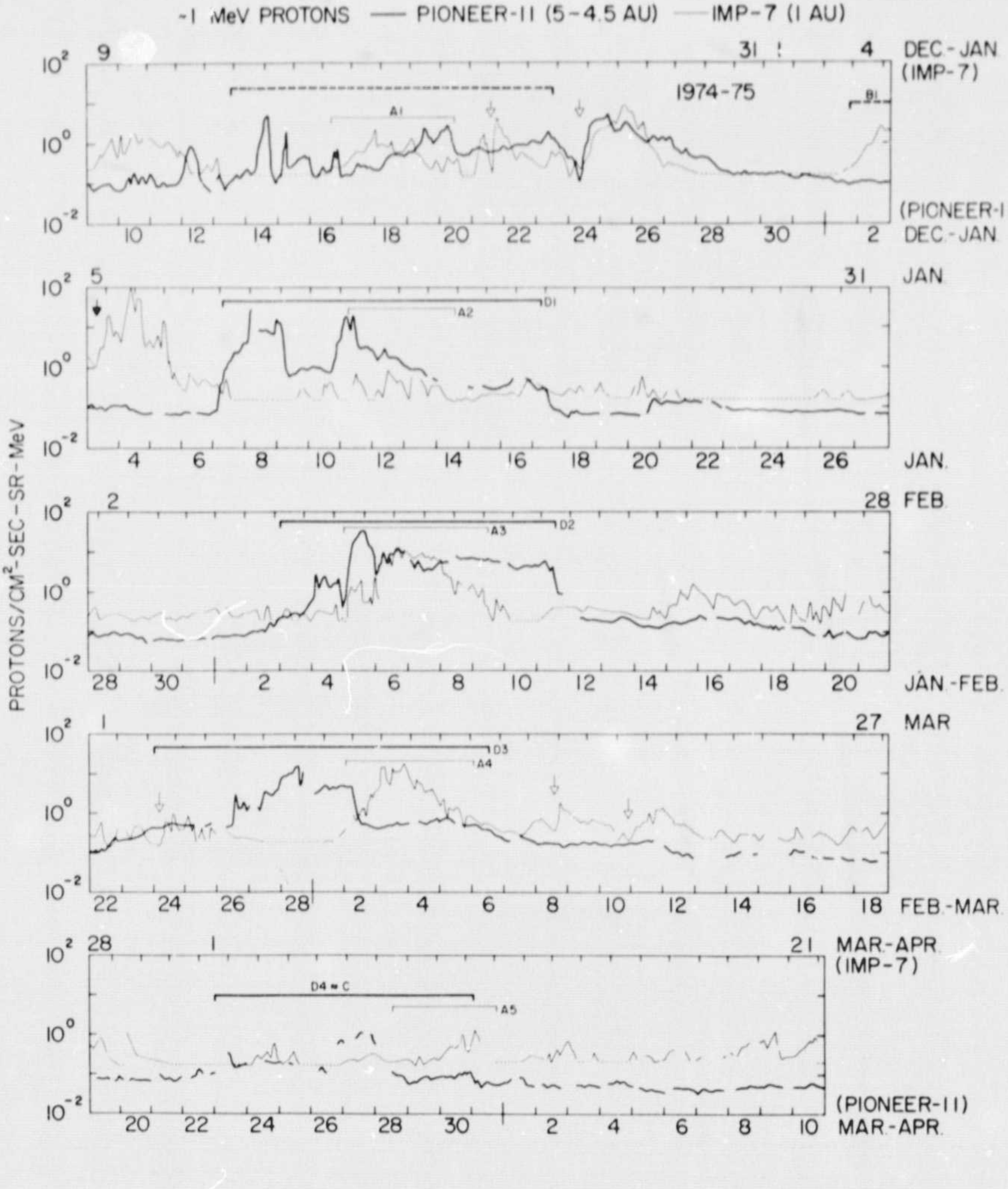
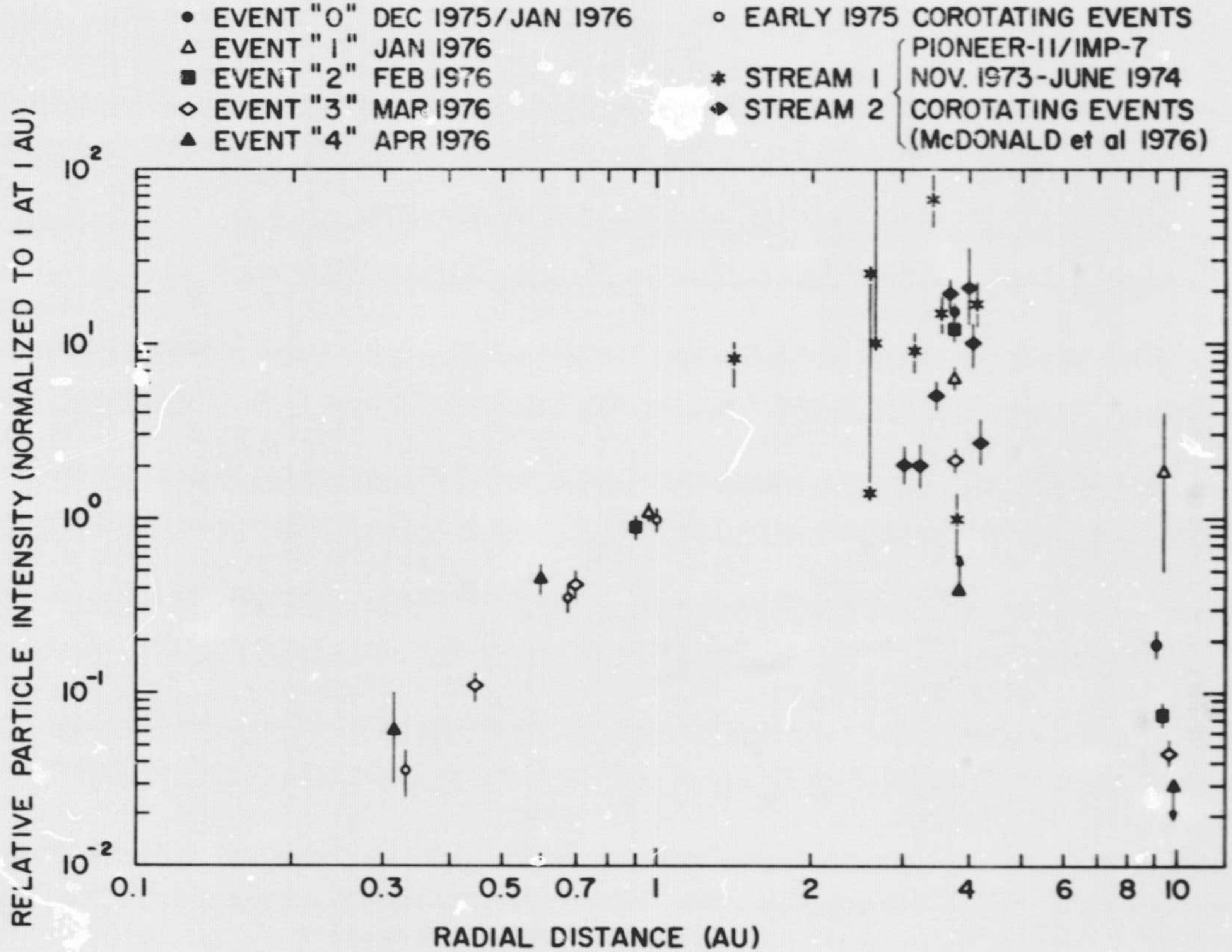

~1 MeV PROTONS — PIONEER-11 (5~4.5 AU) — IMP-7 (1 AU)
PROTONS/CM²-SEC-SR-MeV
1974-75
DEC-JAN (IMP-7)
(PIONEER-11)
DEC-JAN
A1
B1
JAN.
A2
D1
FEB.
JAN-FEB.
A3
D2
MAR
FEB.-MAR.
D3
A4
MAR-APR. (IMP-7)
MAR-APR.
D4 = C
A5

Fig. 4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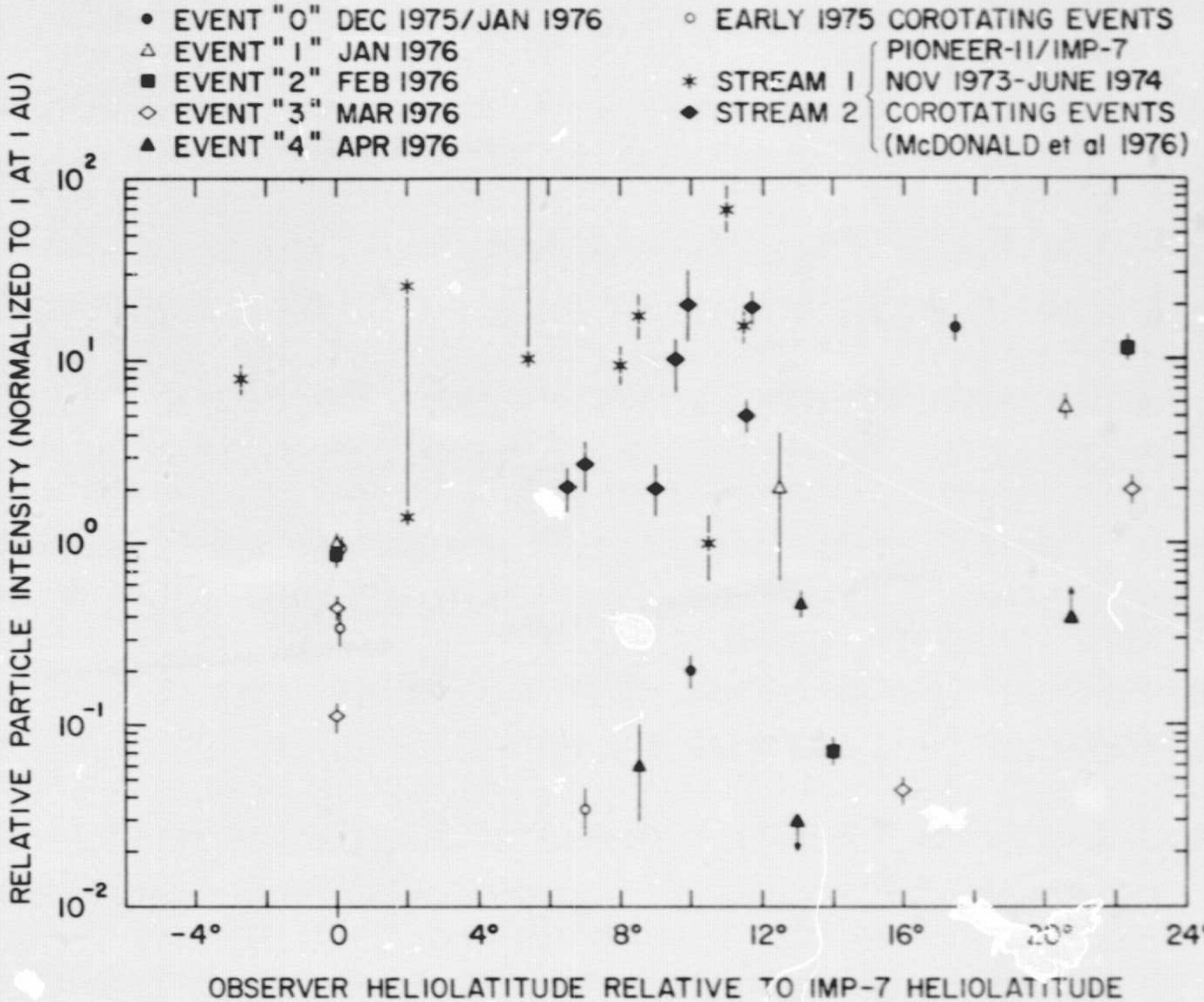
△ EVENT "1" JAN 1976
■ EVENT "2" FEB 1976
◇ EVENT "3" MAR 1976
▲ EVENT "4" APR 1976
○ EARLY 1975 COROTATING EVENTS
✱ STREAM 1
◆ STREAM 2
PIONEER-11/IMP-7
NOV. 1973-JUNE 1974
COROTATING EVENTS
(McDONALD et al 1976)
RELATIVE PARTICLE INTENSITY (NORMALIZED TO 1 AT 1 AU)
10^2
10^1
10^0
10^{-1}
10^{-2}
0.1
0.3
0.5
0.7
1
2
4
6
8
10
RADIAL DISTANCE (AU)

Fig. 5



EVENT "0" DEC 1975/JAN 1976
EVENT "1" JAN 1976
EVENT "2" FEB 1976
EVENT "3" MAR 1976
EVENT "4" APR 1976
EARLY 1975 COROTATING EVENTS
STREAM 1
STREAM 2
PIONEER-11/IMP-7
NOV 1973-JUNE 1974
COROTATING EVENTS
(McDONALD et al 1976)
RELATIVE PARTICLE INTENSITY (NORMALIZED TO 1 AT 1 AU)
OBSERVER HELIOLATITUDE RELATIVE TO IMP-7 HELIOLATITUDE

Fig. 6

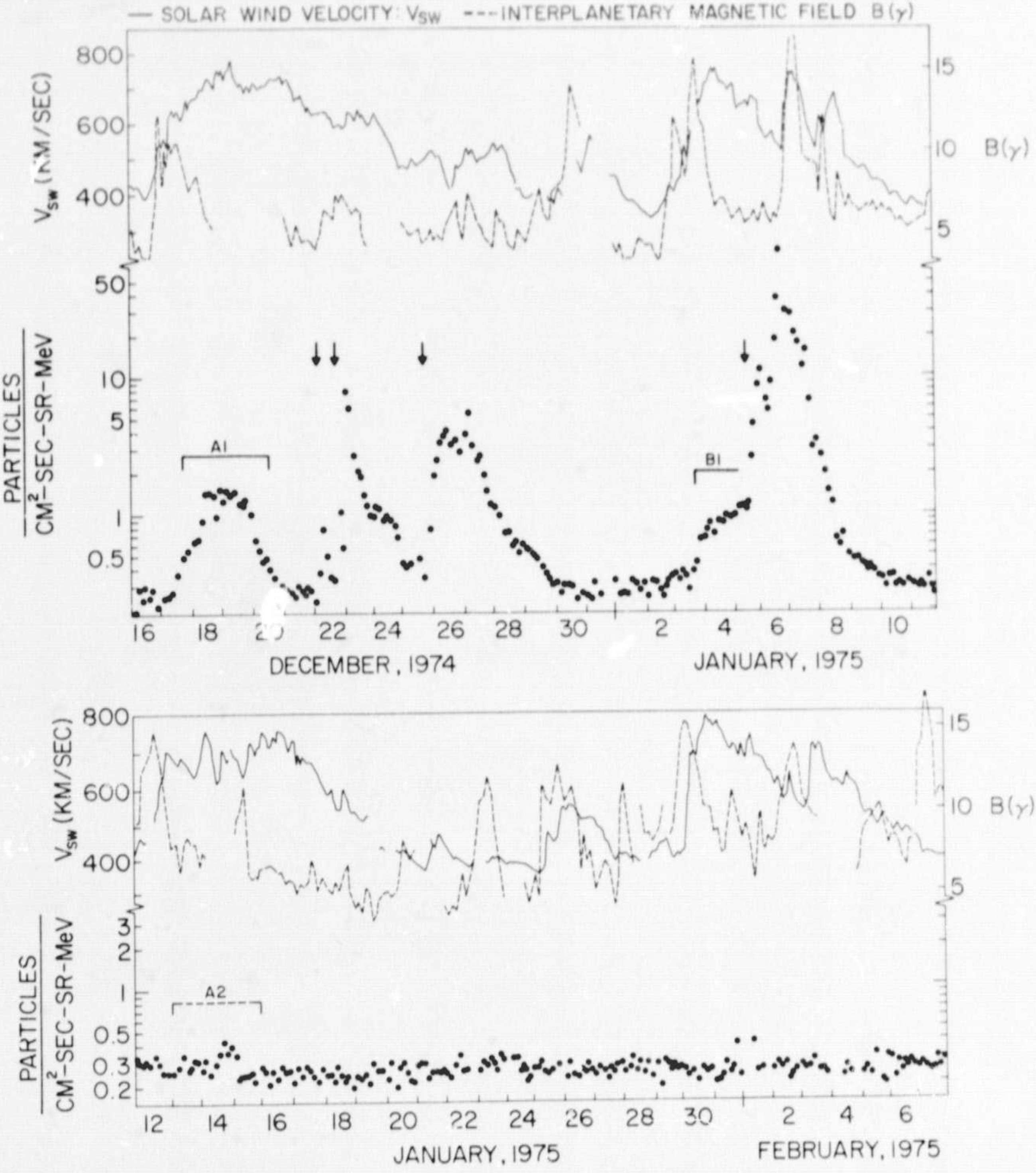
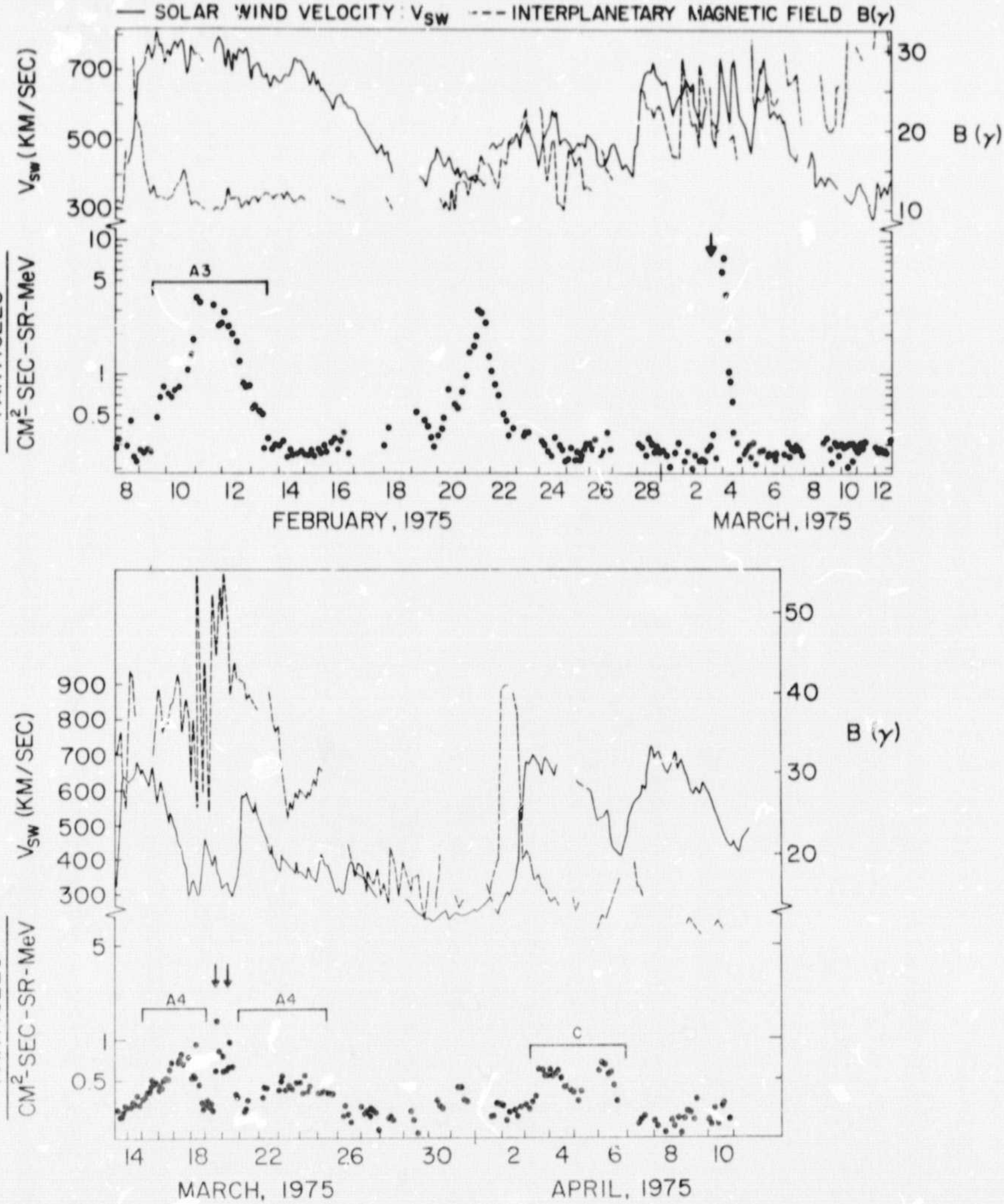

— SOLAR WIND VELOCITY: V_{SW} ---INTERPLANETARY MAGNETIC FIELD B(γ)
V_{SW} (KM/SEC)
800
600
400
15
10 B(γ)
5
PARTICLES / CM²-SEC-SR-MeV
50
10
5
1
0.5
A1
B1
16 18 20 22 24 26 28 30 2 4 6 8 10
DECEMBER, 1974
JANUARY, 1975
V_{SW} (KM/SEC)
800
600
400
15
10 B(γ)
5
PARTICLES / CM²-SEC-SR-MeV
3
2
1
0.5
0.3
0.2
A2
12 14 16 18 20 22 24 26 28 30 2 4 6
JANUARY, 1975
FEBRUARY, 1975

Fig. 7



— SOLAR WIND VELOCITY: V_{SW} --- INTERPLANETARY MAGNETIC FIELD B(γ)
V_{SW} (KM/SEC)
700
500
300
30
20
10
B(γ)
10
5
1
0.5
PARTICLES / CM^2-SEC-SR-MeV
A3
8
10
12
14
16
18
20
22
24
26
28
2
4
6
8
10
12
FEBRUARY, 1975
MARCH, 1975
900
800
700
600
500
400
300
50
40
30
20
B(γ)
V_{SW} (KM/SEC)
5
1
0.5
PARTICLES / CM^2-SEC-SR-MeV
A4
A4
C
14
18
22
26
30
2
4
6
8
10
MARCH, 1975
APRIL, 1975

Fig. 6

BIBLIOGRAPHIC DATA SHEET

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12. Sponsoring Agency Name and Address		13. Type of Report and Period Covered TM
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16. Abstract

The radial gradient of long-lived, corotating energetic particle streams is measured using observations of .9-2.2 MeV protons from Helios 1 and 2 between .3 AU and 1 AU, IMP 7 at 1 AU, Pioneer 11 at 3.8 AU and Pioneer 10 between 9 AU and 10 AU. These studies cover several time periods from mid-1973 to mid-1976. A positive gradient of ∿350% per AU is found between .3 AU and 1 AU. Between 1 AU and some 3-5 AU, the gradient is variable with an average value of 100% per AU which is consistent with the earlier statistical results obtained from the IMP 7 and Pioneer 11 data. A comparison between measurements at 9 AU and ∿4 AU shows a negative gradient which is variable from -40 to -100% per AU. Possible solar latitudinal effects on these gradient studies are also discussed. Using solar wind and magnetic field data from Helios 1 between 1 AU and .3 AU, the relation between corotating energetic particle events in the inner solar system and the interplanetary medium is examined. It is found that the energetic particles are contained inside the high speed solar wind stream in a region adjacent to the interaction region between low speed and high speed streams.

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