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ABSTRACT

Co-rotating proton and electron streams are the dominant type of low-energy (i.e. 0.1-10 MeV/nucleon) particle event observed at 1 A.U. The radial dependence of these events has been studied between 1 and 4.6 A.U. using essentially identical low-energy detector systems on IMP 7, Pioneer 10 and Pioneer 11. It had been expected that at a given energy the intensity of these streams would decrease rapidly with heliocentric distance due to the effects of interplanetary adiabatic deceleration. Instead it is observed that from event to event the intensity either remains roughly constant or increases significantly (more than an order of magnitude) between 1 and 3 A.U. It appears that interplanetary acceleration processes are the most plausible explanation. Several possible acceleration models are explored.

Cosmic-ray experiments on Pioneers 10 and 11 and on IMPs 7 and 8 constitute a unique network to explore the properties of galactic and solar cosmic rays in the heliosphere. In this paper, this network is used to explore the radial dependence of low-energy co-rotating nucleons and electrons between 1 and 4.6 A.U. They represent the dominant type of low-energy(i.e.~0.1-10 MeV) event observed at 1 A.U. and have characteristics that are significantly different from those of flare-associated increases. The rise and decay times are generally slower and more symmetric with little or no systematic velocity dispersion observed during the onset phase. They typically last for 4-10 days, suggesting widths of 50-130° at 1 A.U. While there is no apparent correlation with solar flare and type IV radio emission, there is an association with increased geomagnetic activity, changes in the interplanetary medium, and with decreases in the galactic cosmic-ray intensity. The energy spectra of the co-rotation events are sufficiently steep at high energies so that they are rarely detected above 20 MeV. In many cases the electron peak intensity (at ~40 keV) may occur several hours before the maximum proton flux. Multi-spacecraft studies suggest that transverse diffusion of particles across interplanetary magnetic field lines in these events is negligible. A comprehensive survey of these events has been given by McCracken and Rao (1969). In addition the following references are representative of many studies undertaken in this area: Bryant et al. 1963; Fan et al. 1966; Lin and Anderson 1967; Fan et al. 1968; Anderson 1969; McDonald and Desai 1971; Krimigis et al. 1971; and Roelof and Krimigis 1973.

It was expected that these co-rotating streams would diminish rapidly with radial distance due to both spatial effects and adiabatic energy-loss processes. (Gleeson et al. 1971; Gleeson 1971) The Pioneer 10 and 11 spacecraft with IMPs 7 and 8 at 1 A.U. provide an ideal means of studying the propagation dynamics of these co-rotating streams. The Pioneer trajectories are such that out to ~3 A.U. each spacecraft is within 25° of the nominal interplanetary magnetic field line intercepting the earth (assuming a plasma velocity of 400 km/sec). The Goddard-University of New Hampshire detector systems on Pioneers 10 and 11 (Trainor et al. 1974) measure differential proton energy spectra from 0.2 - 500 MeV and electrons from 0.1 - 8 MeV. (At low flux levels the electron data from 0.1 - 3 MeV is affected by the plutonium-fueled RTG spacecraft power generator). For this study the Pioneer LET-II telescope is used to study 1.2 - 2.1 MeV protons (and 0.3 - 2.1 MeV/nucleon alphas) stopping in the 50μ front detector. There are also two LET-II systems on IMP 7 which are essentially identical to the Pioneer system except the corresponding energy interval is 1.27 - 2.1 MeV. The geometric factor for these telescopes is .015 cm^2-ster.

The first 3.6 months of data from Pioneer 11 along with the corresponding data from IMP 7 is shown in Figure 1 for the 1.2 2.1 MeV protons. A small solar particle event which started several days after the initial experiment activation provides direct intercomparison of the data sets at a time when the separation is negligible. The agreement is good with the IMP 7 fluxes being just below those of Pioneer, as expected from the 4% higher threshold of the IMP detector.

This correspondence between the data sets remains reasonable until Pioneer 11 reaches 1.3 A.U. in June 1973.

There is an increase at Pioneer 11 on 5 June that is a factor of ~12 larger than at IMP. Events in mid-June and July are roughly comparable at the two locations. In late July there is a flare-associated event which is larger at IMP 7 than it is at 1.9 A.U. This data set certainly does not reveal the systematic decrease in the intensity of the co-rotating streams which had been predicted. To study the behavior of the streams at greater heliocentric distances, the same Pioneer 11 and IMP 7 energy intervals are shown in Figure 2 for the six-month period from 1 November 1973 to 1 May 1974 during which Pioneer 11 moved from 2.68 to 3.94 A.U. The Jovian electron data indicates the co-rotation time between the two spacecraft was less than 1 day in mid-December and was on the order of 5 days in early April with Pioneer 11 leading IMP 7. Notice that the flare-associated increase on 2 November 1973 is reduced by a factor of 50 between IMP 7 and Pioneer 11.

The remaining 14 particle increases, which have peak fluxes at either IMP 7 or Pioneer 11 > 1 proton/cm^2-sec-ster-MeV in this 6-month period appear to be co-rotating streams. Three of these (nos. 2,8, and 12) have approximately the same peak intensity at both spacecraft (within ± 25%), 10 are larger at Pioneer 11 (nos. 3,4,5,6,7,9,10,11,13,and 14), and 1 is larger at IMP 7 (no. 1). In most cases the Pioneer 11 events are larger by a factor of 10 to 20. Because of the large distance between the two spacecraft it is not always clear which events on IMP 7 are associated with the Pioneer-11 events. This, however, does not alter the conclusion that statistically there is a strong tendency for the Pioneer 11 events to be larger than those on IMP 7. This large increase in intensity is remarkably different from the conventional expectations that adiabatic energy loss processes associated with convection in the expanding solar wind would reduce these streams to negligible proportions by 3 A.U. The solar-wind transit time between 1 and 3 A.U. is on the order of 10 days and the co-rotation delay ranges up to 5 days. Significant temporal variations in the structure of these streams could be expected during these times. Nevertheless, over more than seven solar rotations, there is only one case where the streams are substantially larger at 1 A.U. than at 3-4 A.U. Many of the Pioneer-11 events from January-April 1974 display a rapid rise time. However, there is no evidence for any velocity dispersion from 0.2 - 5 MeV, nor is there any indication at either spacecraft of a flare-associated event.

It is possible to use Pioneer-10 and -11 data to establish some limits on this growth region. In Figure 3 the Pioneer-10 and -11 LET-II data are plotted with the Pioneer-11 data being for the identical energy interval and time period as that of Figure 1. The co-rotation time between these two spacecraft is expected to be very large (see Teegarden et al. 1974 for a plot of the two spacecraft trajectories). Therefore the data sets have been aligned using the Pioneer 11 "step" event of 15 July 1973 and a similar but smaller Pioneer 10 event on 30 July 1973. Note that this 14-day displacement brings the data from the two widely separated spacecraft into good agreement. In general the Pioneer-10 events are more diffuse and are the same or smaller in amplitude than the corresponding events at Pioneer 11. During most of the period December 1972 to January 1973 when Pioneer 10 passed between 3 and 4 A.U., interplanetary conditions appeared quieter than the corresponding passage of Pioneer 11 through this region, with fewer particle increases at either location.

As noted previously the 1.2 - 2.1 MeV LET-II interval also responds to alpha particles between 0.3 - 2.1 MeV/nucleon. At higher energies multi-parameter analysis of the Pioneer-11 data reveals that at 3-5 MeV/nucleon, the He/P ratio is 3-5%. This suggests that there will be substantial contributions to the 1.2 - 2.1 MeV proton level from low-energy He. Comparison with other detector systems with different foil thickness suggests that alphas are not the dominant component. Preliminary analysis of the Pioneer-11 data indicates there is no simple representation of the spectra between 0.2 - 10 MeV. The range from 0.4 - 10 MeV is consistent with an exponential in energy of the form $\exp(-T/T_o)$ as previously reported by McDonald and Desai (1971) with $T_o \sim 1$ MeV. Below 400 keV the spectrum rises more steeply than this. However, the IMP-7 and Pioneer-11 LET-II systems have identical response to both alphas and protons, so the basic conclusion on the growth of these streams remains unchanged. The Pioneer-11 multi-parameter 3.4 - 5.2 MeV proton data in Figure 4 is unaffected by helium and shows essentially the same time structure as seen by the low-energy component (Figure 2).

It is necessary to establish that these increases are not of Jovian origin. The dramatic increases in MeV Jovian electrons seen on Pioneer 10 and 11 are not observed for protons. Some Jovian proton increases have been reported (Simpson et al. 1975; Trainor et al. 1975), but they are smaller and much less frequent than the electron increases. Furthermore, an anti-correlation has been established between co-rotating proton streams and Jovian electron increases seen at 1 A.U. (McDonald et al. 1972). In Figure 4 the Pioneer-11 fluxes of MeV electrons and protons are compared for the six-month period extending from December 1973 to May 1974. No apparent correlation between the two sets of increases exists. Thus, there appears to be no convincing evidence at this time to support a Jovian origin for these particles. Figure 4 is a further demonstration of the dynamic conditions in interplanetary space. There are only a few days in the six-month period when the 3.4 - 5.2 MeV proton component approaches quiet-time levels.

Using the data from Zond 3 and Venus 2 during the 1965-66 period, Vernov et al. (1970) found a positive gradient of > 200%/A.U. for 1 - 5 MeV protons. They suggested that this may occur when the interplanetary magnetic field at great distances from the sun "becomes chaotic and the process of proton accumulation takes place." In the same paper the authors note the frequent association of co-rotating streams with Forbush decreases and raise the possibility that the 1-MeV protons are accelerated by the inhomogeneties of the solar wind. In the multi-spacecraft study of Roelof and Krimigis (1973) some 6 of their events were classified as "evolving" with continuing solar acceleration. It would appear probable that some of these represent the same type of phenomena discussed here.

The most plausible hypothesis available to explain the growth of these nucleon streams is interplanetary acceleration. Several forms of interplanetary acceleration have been studied in the past. One of these, particle acceleration by interplanetary shock waves, is reasonably well understood (see for example Sarris et al. 1974). There may be standing shocks between slow and fast solar-wind regions which could play a role in the present observations. A second possibility has been suggested by Jokipii (1971) and by Wibberenz and Beuermann (1971) who demonstrated that second-order Fermi acceleration could be an important process for low-energy solar particles in the interplanetary medium. This was originally postulated to explain the observations of Murray et al. 1971, that a feature of the proton energy spectra in a small flare event moved toward lower energies with a time-constant much longer than expected from adiabatic deceleration. Invoking magnetic irregularities moving in both directions along interplanetary field lines with the Alfven velocity V_A, Jokipii (1971) obtained the following expression for the rate of Fermi acceleration:

$$\frac{1}{T}\frac{dT}{dt} \approx \frac{8}{3}\frac{V_A^2}{K_{11}} = \frac{2B^2}{3\pi n m_p K_{11}} = \frac{1}{\tau_F}$$

T = Particle kinetic energy

K_{11} = Parallel diffusion coefficient

B = Magnitude of the interplanetary magnetic field

n = proton number density in the solar wind

m_p = mass of the proton

τ_F = characteristic acceleration time

Taking $n = 4$ protons/cm^3, $B = 10^{-4}$ gauss, $K_{11} = 5\times10^{19}$ cm^2-sec gives $\tau_F \approx 44$ hours. These values are appropriate to disturbed conditions.

Competing with this effect is adiabatic cooling given by

$$\frac{1}{T}\frac{dT}{dt} = -\frac{2}{3}\vec{\nabla} \cdot V = \frac{1}{\tau_{ad}}$$

For spherically symmetric expansion and V = 500 km/sec, $\tau_{ad} \approx 60$ hours. These estimates indicate τ_F and τ_{ad} can be of the same order.

Preliminary examination of the plasma data at 1 A.U. reveals that most of these co-rotating increases are associated with increases in the plasma velocity. The presence of slower-speed solar-wind streams may inhibit the free expansion of the higher-speed region and reduce the effect of adiabatic energy loss, although there is no evidence in the particle data to support this. This stream-stream interaction also establishes a turbulent interface region which could supply the magnetic irregularities for accelerating the particles. Belcher and Davis (1971) have shown that this interface region is where Alfven discontinuities are largest and where it appears most probable that they are bi-directional along the field lines. Further studies are necessary to confirm that interplanetary Fermi acceleration is an important process and to determine whether it is principally a first-order process associated with shock fronts or a second-order process as proposed by Jokipii (1971). The presence of large field-aligned anisotropies (Krimigis et al. 1971) may be difficult to explain by second-order processes and the value of K_{11} at low energies is not well known.

These processes suggest the possibility that some co-rotating particle increases originate from the suprathermal distribution in the solar wind, and are not accelerated at the sun. This, of course, is a speculative observation on which some light may be shed by the Helios and MVM energetic-particle experiments, as well as by observations of the charge composition of these events. It is expected that this process may occur near any star with a stellar wind. These particles would then constitute an additional component of low-energy particles in the interstellar medium. This component is further evidence that there exists a hierarchy of accelerating mechanisms in nature. This particular one may, in fact, turn out to be the simplest to understand.

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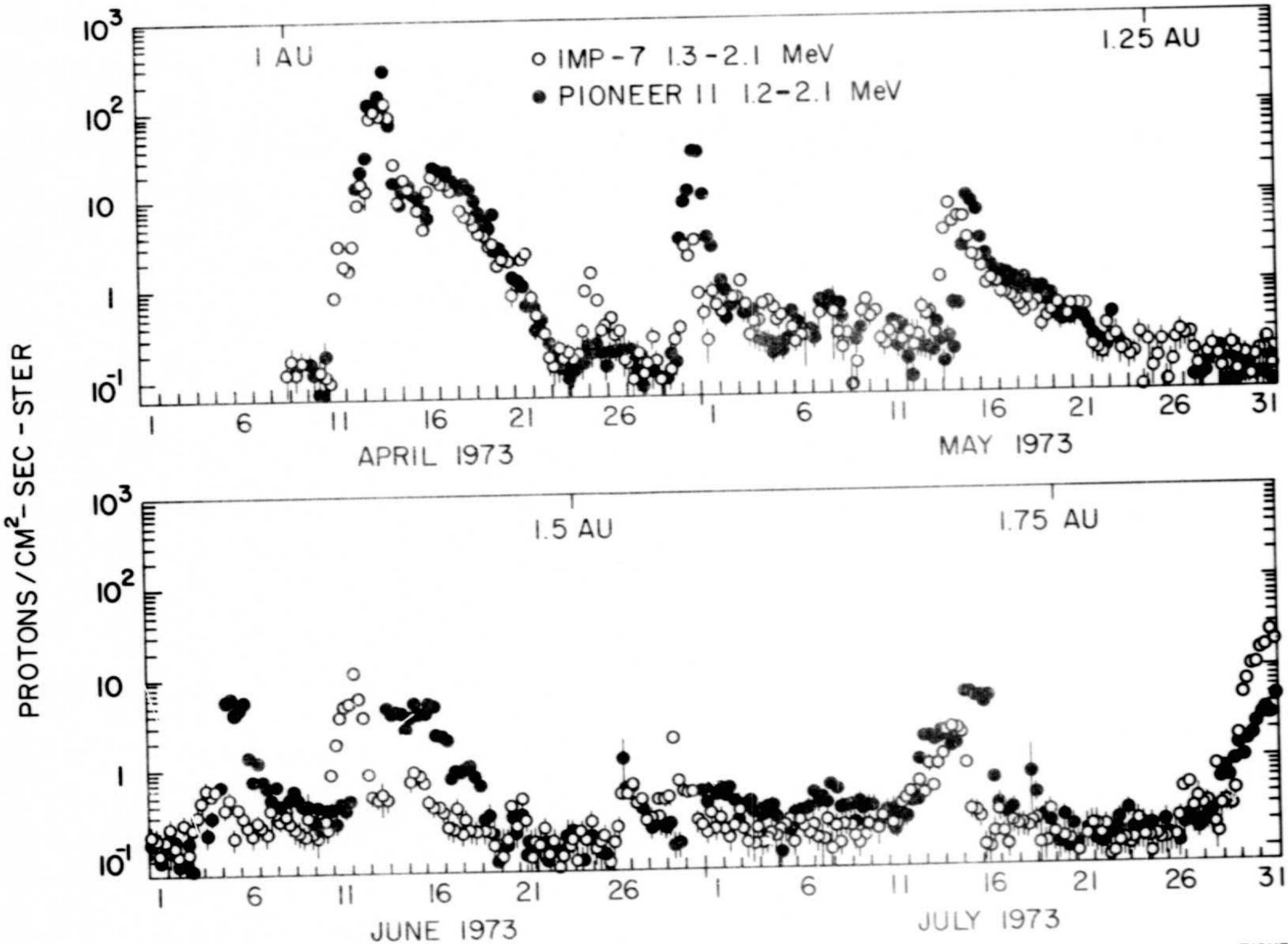
FIGURE CAPTIONS

Figure 1 IMP-7 and Pioneer-11 flux values for 1.2 - 2.1 MeV protons (and 0.3 - 2.1 MeV alphas). Data has been averaged over 6-hour periods. The co-rotation times range from 1 day in early June to 2 days in July with IMP 7 leading Pioneer 11.

Figure 2 IMP-7 and Pioneer-11 flux values for 1.2 - 2.1 MeV protons for 6-month period extending from 1 November 1973 - 1 May 1974. Data has been averaged over 6-hour periods. The increase in early November appears to be the only flare-associated increase in this period. The co-rotating increases which exceeded 1 proton/cm^2-sec.ster-MeV have been numbered. Only one co-rotating event (no. 1) is larger on IMP 7 than on Pioneer 11.

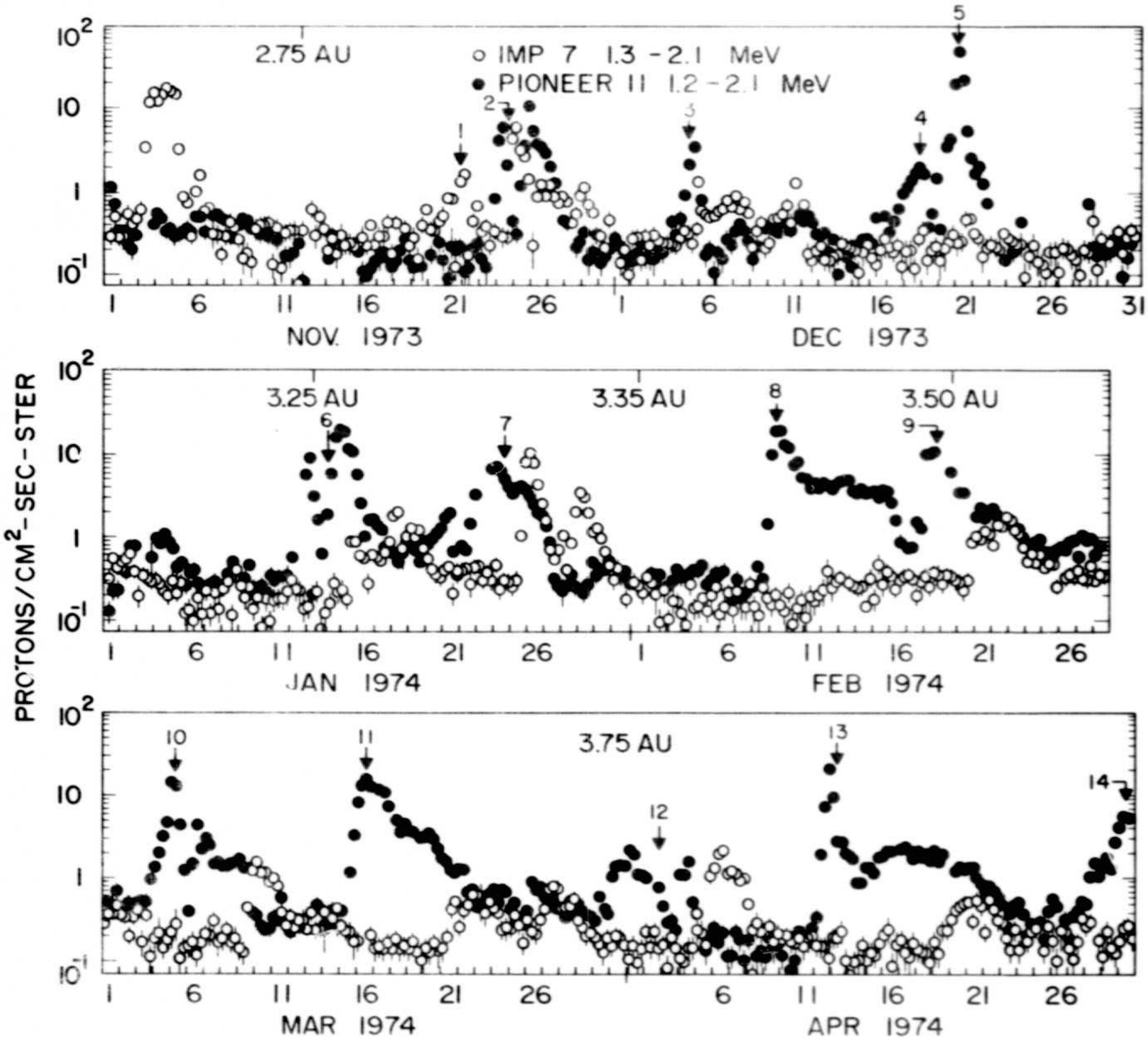
Figure 3 Pioneer-10 and -11 6-hour averages for 1.2 - 2.1 protons for the same period as shown in Figure 1. Pioneer-10 data has been shifted as discussed in the text. (See Teegarden <u>et al</u>. 1974 for trajectory diagram).

Figure 4 Pioneer-11 3-8 MeV electrons and 3.4 - 5.2 MeV, 5.6 - 22 MeV and 24 - 31 MeV protons. The proton data is derived from multi-parameter analysis with no alpha response.



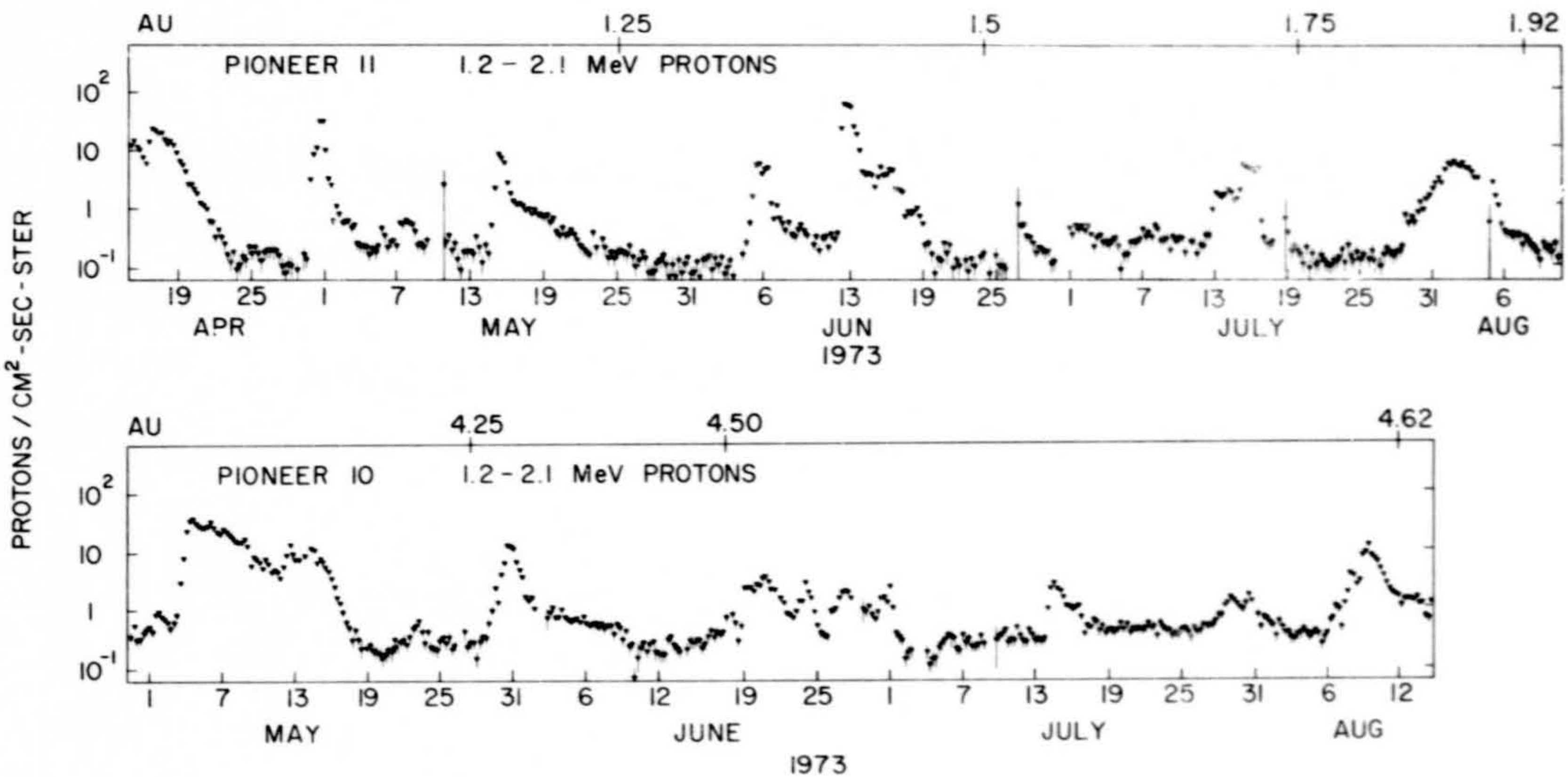
PROTONS / CM²-SEC-STER
10³
10²
10
1
10⁻¹
1 AU
1.25 AU
○ IMP-7 1.3-2.1 MeV
● PIONEER 11 1.2-2.1 MeV
1 6 11 16 21 26 1 6 11 16 21 26 31
APRIL 1973
MAY 1973
1.5 AU
1.75 AU
1 6 11 16 21 26 1 6 11 16 21 26 31
JUNE 1973
JULY 1973

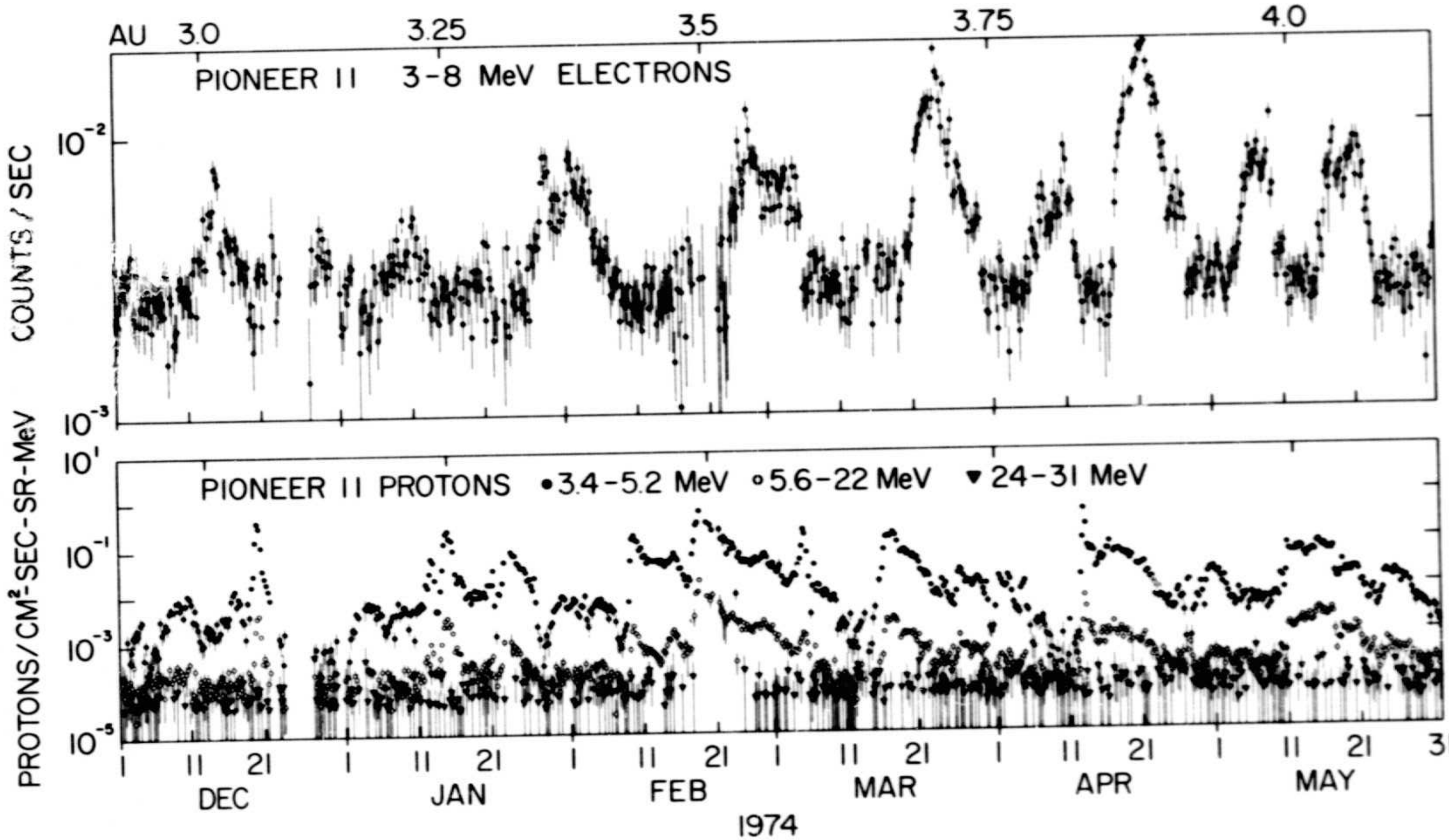
FIGURE 1



2.75 AU
IMP 7 1.3 - 2.1 MeV
PIONEER 11 1.2 - 2.1 MeV
NOV. 1973
DEC 1973
3.25 AU
3.35 AU
3.50 AU
JAN 1974
FEB 1974
3.75 AU
MAR 1974
APR 1974
PROTONS/CM²-SEC-STER

FIGURE 2


PROTONS / CM²-SEC-STER
AU
1.25
1.5
1.75
1.92
PIONEER 11 1.2 - 2.1 MeV PROTONS
10²
10
1
10⁻¹
19 25 1 7 13 19 25 31 6 13 19 25 1 7 13 19 25 31 6
APR
MAY
JUN
JULY
AUG
1973
AU
4.25
4.50
4.62
PIONEER 10 1.2 - 2.1 MeV PROTONS
10²
10
1
10⁻¹
1 7 13 19 25 31 6 12 19 25 1 7 13 19 25 31 6 12
MAY
JUNE
JULY
AUG
1973


AU 3.0 3.25 3.5 3.75 4.0
PIONEER 11 3-8 MeV ELECTRONS
COUNTS / SEC
10^-2
10^-3
PIONEER 11 PROTONS •3.4-5.2 MeV ∘5.6-22 MeV ▼24-31 MeV
PROTONS/CM²-SEC-SR-MeV
10^1
10^-1
10^-3
10^-5
1 11 21 1 11 21 1 11 21 1 11 21 1 11 21 1 11 21 31
DEC JAN FEB MAR APR MAY
1974