SIMULTANEOUS OBSERVATIONS OF COSMIC RAY PARTICLES IN A COROTATING INTERPLANETARY STRUCTURE AT DIFFERENT SOLAR DISTANCES BETWEEN 0.3 AND 1 AU FROM HELIOS 1 AND 2 AND IMP 7 AND 8

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Abstract. From December 1975 to June 1976 we observed an evolving recurrent proton enhancement with IMP 7/8 and Helios 1/2 at different distances from the sun. The corotating character is established over 4 solar rotations. Due to the unique constellation in March 1976 simultaneous measurements were possible which allowed a study of the radial development undisturbed by temporal effects. The intensity variation of the ∿ 4 - 13 MeV protons between 0.43 and 1 AU revealed a sudden increase to a large positive gradient (+329 %/AU) in the leading edge of the event. This value is consistent with a major source outside 1 AU. We suggest an interplanetary acceleration which becomes sufficiently effective within a fast solar wind stream.

1. Introduction. The Pioneer 10 and 11 missions to Jupiter provided for the first time the opportunity to extend the studies on the radial dependence of recurrent proton enhancements over a much larger range of radial distances. McDonald et al. (1975) found that the average recurrent events near 3 AU were up to ∿10 times larger in intensity than the average events observed at 1 AU. Whereas initially a solar origin of these particles had been assumed, McDonald et al. now suggested that interplanetary acceleration was resonsible for the higher intensities observed beyond 1 AU. Barnes and Simpson (1976) reported evidence for interplanetary acceleration of nucleons in corotating interaction regions. In a statistical study, Marshall and Stone (1977) found that in the majority of the events observed at 1 AU the diffusive anisotropy of ∿1.6 MeV protons was towards the sun, along the interplanetary magnetic field, indicating that there was a source of particles outside 1 AU and a sink inside.

In this paper we present measurements of proton intensities in corotating events, taken by two spacecraft inside 1 AU simultaneously and by two spacecraft at 1 AU with only a very short time delay.

2. Development of the recurrent proton enhancement between January and April 1976. From December 1975 until June 1976 an evolving recurrent proton enhancement has been observed in interplanetary space. This period is characterized by a very low level of solar activity only a few months before the solar minimum. Between January 12 and March 21, 1976 no solar flare of importance 1f or larger had been observed. Figure 1 shows the intensity-time history of 4.0 - 12.5 MeV protons as measured by the Caltech Electron/Isotope Spectrometer on board IMP 8. The 4 panels of figure 1 show the complete Carrington rotations 1637 through 1640. The Carrington longitude scale on the bottom describes the magnetic field line connection of IMP 7/8 to the solar surface assuming a constant solar wind velocity of 550 km/s.

The significant feature of figure 1 is the recurrence of a proton intensity enhancement with a period of ∿ 27 days over 4 solar rotations centered around 280° Carrington longitude. The event develops considerably during three subsequent solar rotations. The slow increase in January lasts for nearly 10 days with its maximum after 6 days. The maximum intensity is 4 x 10^1 protons/m^2s sr MeV. One rotation later, in February 1976, the maximum intensity is reached after a rise time of only four days. The first and second peak which are separated by three days show nearly the same intensity of 3 x 10^2 protons/m^2s sr MeV. The decay appears to be much slower and shows two additional humps.

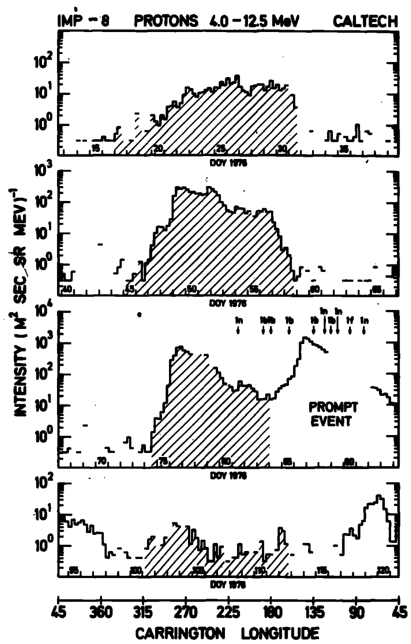

Fig.1: Recurrence of an intensity enhancement (shaded area) of 4.0-12.5 MeV protons measured by IMP 7/8 over 4 solar rotations (day 13-120, 1976).

During the third solar rotation the intensity increases up to 7 x 10^2 particles/m^2s sr MeV within 2.5 days. Here the first peak is much more pronounced than the following peaks. The decay phase, however, is disturbed by a prompt solar particle event due to a series of flares between March 21 and March 31, 1976. In April the corotating feature has weakened by two orders of magnitude. However, the peak appears at the same Carrington longitude as before. This disturbance of the corotating structure might be related to the series of flares which ended 12 days before the onset.

While the corotating structure seems to develop for 3 complete solar rotations and to decay thereafter significant features persist at nearly the same Carrington longitude for 3 or 4 solar rotations. This demonstrates the recurrent character of the intensity enhancements (shaded area in figure 1). For a more detailed discussion we shall concentrate in the following on the increase between March 12 and March 20, 1976 (days 72-80).

3. Spacecraft constellation. The March 1976 corotating event has been observed by 4 spacecraft simultaneously. The spacecraft constellation for March 15 is given in figure 2. Helios 1 was closest to the sun at a radial distance of 0.43 AU and a heliographic latitude of -7.1°. Helios 2 was located at a solar distance of 0.67 AU and a latitude of -7.2°. Both probes were connected via interplanetary magnetic field lines to the same region on the sun at 268° Carrinton longitude. The earth orbiting satellites IMP 7 and 8 were at a solar distance of 0.994 AU and a heliographic latitude of -6.5°. On March 15 these satellites were probably in a regime of relatively low solar wind velocity and connected to the corona at 305° Carrington longitude.

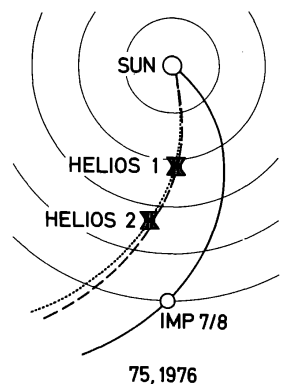

Fig.2: Constellation of HELIOS 1/2 and IMP 7/8 on March 15, 1976.

This spacecraft constellation is unique in so far as Helios 1 and Helios 2 are located at different solar radial distances but on the same interplanetary magnetic field line. We wish to point out that this includes the longitude as well as the latitude of the magnetic field line connection to the sun. Only ∿ 30 hours later the same interplanetary magnetic field line intercepts the IMP 7 and IMP 8 satellites. These relative spacecraft positions allow the radial development of the event to be studied undisturbed by temporal effects.

4. Instrumentation. The observations on which this paper is based were made by the Caltech experiments on board IMP 7 and 8 and by experiments of the University of Kiel on board Helios 1 and Helios 2. The detector telescope of the Helios 1 and 2 instruments is described in detail by Kunow et al. (1975) and by Kunow et al. (1977). In this paper we present coincidence data of detectors 1 and 2. The original countrates were corrected for background using two-dimensional pulse height information of extended time periods. The EIS experiment on board of IMP 7 and 8 is described by Hurford et al. (1974) and Mewaldt et al. (1976). The data presented in this paper are based on two-parameter particle identification.

An intercalibration of all 4 instruments was performed for the corotating event periods in December 1975 and January 1976 when both Helios spacecraft were outside 0.9 AU and within an azimuthal distance of 24° from the earth. Taking into account the corotation delay all 4 instruments measured the same intensities to within ± 15 %.

5. The March 1976 Corotating Event. The March 1976 corotating event, already introduced above, is shown in more detail in figure 3. Prior to the onset of the event a sector boundary sweeps past Helios 1 and 2 (G. Musmann and F. Neubauer, private communication). The intensity time profiles of 4 to 13 MeV protons are presented by 2-hour averages between March 12 and March 20, 1976. The profiles are similar at the three radial distances 0.43, 0.67 and 1.0 AU. The intensity rises to the main maximum within about

50 hours. The event shows the double hump structure (best evident at 1 AU) frequently observed in corotating events at larger solar distances (Barnes et al., 1976). We have visually identified the structures 3, 4 and 5 which are common to all three profiles. Application of the backmapping technique using preliminary solar wind velocities (courtesy H. Rosenbauer, R. Schwenn) results in the same Carrington longitudes within $\pm$ 3° for the corresponding structures. Additional times have been chosen for identical Carrington longitudes and are marked 1, 2, 6 and 7. The increasing phase and the first maximum coincide roughly with the increase and maximum of a high speed solar wind stream. The decreasing phase lasts for 4 days before it is masked by a prompt solar event (see figure 1). Special consideration should be given to the large step between marks 2 and 3 indicating a moderate intensity increase by a factor of 2.5 at the position of Helios 1, but a drastic intensity increase by a factor of ∿10 at 1 AU.

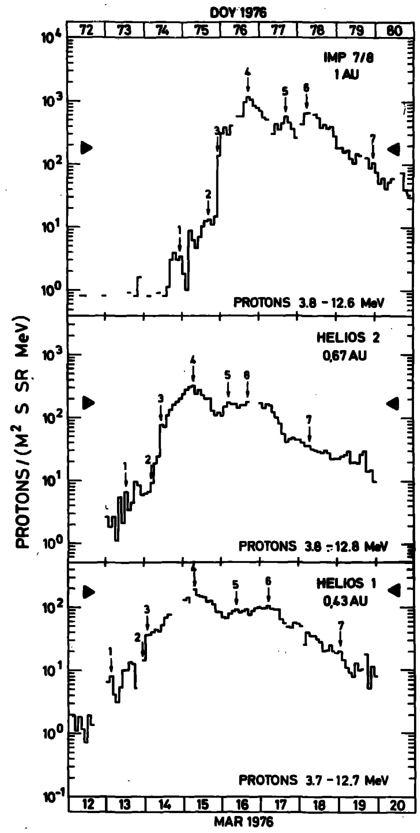

Fig.3: Two-hour averages of proton intensities measured simultaneously at three different radial distances. Marks 1 through 7 denote measurements on the same interplanetary magnetic field line. Note that the energy interval for IMP 7/8 data has been adjusted slightly from that shown in fig. 1 to agree more closely with the Helios instruments.

Note also the radial dependence of the intensity. The intensity level of the main peak as observed by Helios 1 is marked by solid triangles in each panel. The peak intensity of 4-13 MeV protons increases by a factor of 5.6 as the radial distance varies from 0.43 to 1.0 AU. The radial dependence of the intensity at the 7 marked levels in the profiles, which correspond to measurements on essentially the same interplanetary magnetic field line is shown in figure 4. The Carrington longitude changes from 310° to 227° between positions 1 and 7. The intensity is plotted on a logarithmic scale versus radial distance on a linear scale. The measurements can be fitted reasonably well by a straight line. Thus we can describe the radial dependence of the intensity by radial gradient $g = \frac{1}{I} \times \frac{dI}{dr}$ which is independent of r. Starting from the onset of the event (marked 1) the radial gradient g is negative: g = -(175 $\pm$ 70) %/AU. The gradient increases with decreasing Carrington longitude, and switches suddenly to large positive values within less than 5 hours in coincidence with the large step between position 2 and 3. For the remaining part of the observable event (until it is masked by a prompt solar event on March 21) the gradient changes only little. For the main peak e.g. the gradient is g = + (329 $\pm$ 20) %/AU.

It should be pointed out that from approximately noon on day 74 until noon on day 77 (IMP 8) and from approximately noon on day 76 until the end of day 79 (IMP 7), the IMP instruments were inside the earth's magnetopause ∿ 30 earth radic down the magnetotail. Intercomparison of IMP - 7 and 8 data during these periods indicates that the absolute intensities of 4 to 13 MeV protons were affected by $\lesssim$ 20 % by the presence of the magnetopause.

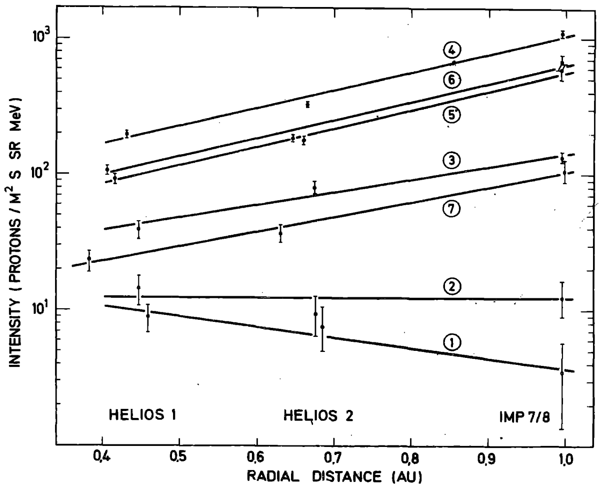

Fig. 4: Radial dependence of the proton intensity at the 7 marked levels of Fig. 3.

6. Discussion.

The material presented here is not sufficient to definitely confirm or rebut existing models about the origin and nature of corotating events. The observed positive radial gradients certainly exclude a direct solar origin combined with pure interplanetary propagation, where "pure" means that there is no local interplanetary acceleration.

Let us for simplicity assume an outer source of particles produced well beyond the points of observation discussed in this paper. These particles penetrate into the inner solar system quite in the same way as particles of galactic origin. Under stationary conditions, a particularly simple form of the transport equation is given by the force-field approximation (Gleeson and Axford, 1968), which is valid when the radial streaming S_r is zero. (This condition might apply here in contrast to particles of galactic origin in this energy range because of the steep energy spectrum, and, as a consequence, of the large Compton-Getting factor). From an experimental viewpoint, a vanishing radial streaming is related to a vanishing anisotropy in the radial direction. Preliminary analysis indicated that the anisotropies are small, consistent with the observations of Marshall and Stone (1977). If over the energy range 4-13 MeV we assume a power law spectrum $\sim E^{-\gamma}$, we have $\gamma \simeq 4$. This gives a Compton-Getting factor C = 3.3.

The force-field equation

$$S_r = CVU - K_r \frac{\partial U}{\partial r} = 0$$

allows to relate the gradient $G_r = \frac{1}{U}\frac{\partial U}{\partial r}$ to the diffusion coefficient K_r, once C and V are known. Inserting G_r = 329 %/AU V = 550 km/sec and C = 3.3, we obtain $K_r = 9.6 \times 10^{20}$ cm^2 s^{-1}. Let us take $v/c = \beta = 0.1$ as a representative proton velocity for the energy range 4-13 MeV. This gives us for the radial mean free path λ_r = 0.06 AU which is in good agreement with the average mean free path for cosmic ray particles as deduced from solar cosmic ray events (Wibberenz, 1974), and with that deduced by Marshall and Stone (1977) for ∿1.6 MeV recurrent events at 1 AU.

The estimate does not explain the existance of recurrent events, but it shows that the observations are consistent with a major source for these particles outside 1 AU. The onset of the positive radial gradient in coincidence with the leading edge of a fast solar wind stream indicates that the acceleration process becomes sufficiently effective within a fast stream. In the model suggested here the constancy of the radial gradient both with respect to radial distance and to longitudinal phase might be related to the constancy of the cosmic ray diffusion coefficient. The characteristic intensity profile may be due either to the boundary and injection conditions or to the variation of wave-particle interactions with phase within a fast solar wind stream.

7. References

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