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Low-flux spatial structures of MeV protons at 1–10 AU during quiet-time periods

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Abstract. Time variations of 0.5-20 MeV/nucleon quiet-time populations of energetic protons and He nuclei between 1 and 10 AU are considered during solar cycles 21 and 22. The intensity profiles obtained by the IMP-8 satellite, Ulysses, Voyagers 1, 2, and the Pioneer 11 spacecraft exhibited certain pecularities (i.e., large decreases), which appeared to be reasonably similar. The analysis of these decreases of low-energy proton intensity observed at the Earth and in the outer heliosphere revealed the existence of extensive empty spatial structures ('hollows') that contain low energetic particle fluxes. It should be noted that the value of magnetic field strength was also very low inside them. Assuming that these 'hollows' were bounded by Archimedean spiral field lines they spread over at least 10 AU and about 60 degrees in ecliptic longitude. Four empty structures observed in 1978-81 as well as three in 1983 are discussed. The results obtained confirm the suggestion of small cross-field diffusion coefficient of low-energy particles in the inner heliosphere at distances up to 10 AU.

1 Introduction

In addition to recurrent enhancements, Logachev et al. (1999) found recurrent structures containing low fluxes in the interplanetary space near 1 AU. Such low fluxes were observed in 1975 by IMP-8 at 1 AU and by Helios 1 inside 1 AU. It has been assumed that these low fluxes represented the genuine background at solar activity minimum. Although often masked by additional more intense particle fluxes, they were found to exist in the interplanetary space probably all the time, sometimes connected with corotating interference regions, which imitate the corotating nature of low fluxes. In 1975 such low-flux regions spread up to 90° and more in longitude. During high solar activity higher

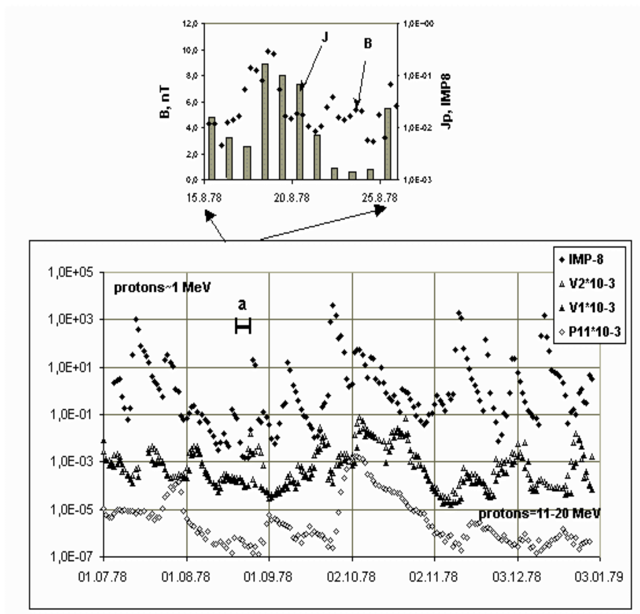

Fig. 1. Time profiles of daily averaged proton fluxes. Upper panel: interplanetary magnetic field at IMP-8.

fluxes from SEP events and other active processes on the Sun and in the interplanetary space very rarely allowed observing low-flux regions, their duration became shorter, and sometimes they entirely disappeared. However, in 1978-81, 83 and 1989-90 in spite of increasing solar activity several time intervals of low fluxes were observed at 1 AU as well as further out at distances up to 10 AU from the Sun.

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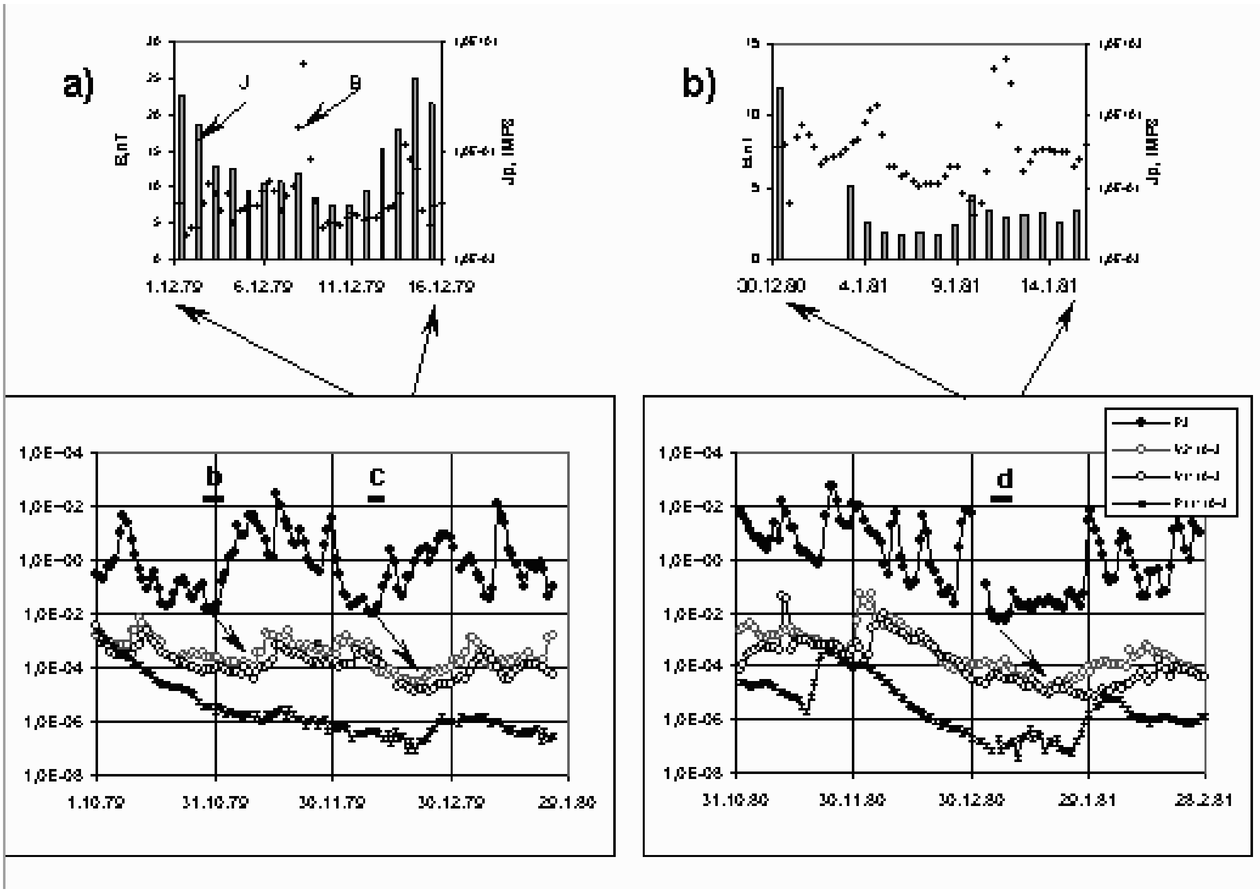

Fig. 2. Time profiles in 1979 and 1981.

2 Observations: 'hollows' - empty spiral spatial structures in the interplanetary space

We searched for characteristic features of low-energy quiet-time proton and He nuclei fluxes using near 1 AU data of the IMP-8 CPME experiment in the energy ranges 0.5-0.96 and 0.97-1.85 MeV per nucleon. Beyond 1 AU, energetic particle information from the LECP experiment aboard Voyagers 1 and 2 and from the Pioneer 11 CPI experiment have been used (proton energy intervals: LECP - 0.57-1.78 MeV, CPI - 11-20 MeV).

Figures 1-3 display ~1 MeV proton intensity time profiles during several time intervals in 1978-81 and in 1983. In each year the lowest fluxes are marked in the upper parts of the Figures 1 and 2 by thick rectangles**.** These large decreases of intensity have been observed on IMP-8 at 1 AU as well as on Voyagers 1 and 2 and on Pioneer-11 (11-20 MeV protons). For all s/c during these time intervals low-energy proton fluxes were found to have intensities well below the yearly average quiet-time intensity but still higher than at the minimum of the SC. It should be mentioned that during these periods a weak magnetic field was observed. The 8-hour averaged interplanetary magnetic field magnitude at 1 AU was low, about 4 to 6 nT during the time of low proton fluxes but increased to 10-30 nT out of

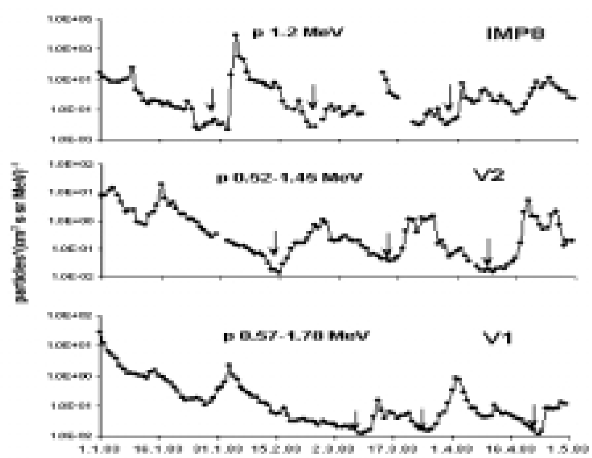

Fig. 3. Low-energy proton fluxes measured by IMP-8, Voyager 1 and 2. Arrows mark time intervals of lowest fluxes.

these intervals (see top inserts in Figures 1 and 2).

In order to check if low fluxes observed at different s/c belonged to the same spatial structure, the time periods when the spatial structure in question that contained low fluxes went past each s/c have been compared. It was found that the temporal delay of the periods having minimum fluxes between each spacecraft corresponded well to the s/c space position and solar wind speed measured at that time. This indicates a reasonable agreement among measurements at different distances and longitudes thus we may assume that these low fluxes corotate with the Sun. Schematic pictures of supposed spatial structures devoid of low-energy particles denoted further as 'hollows' are presented in Figure 4.

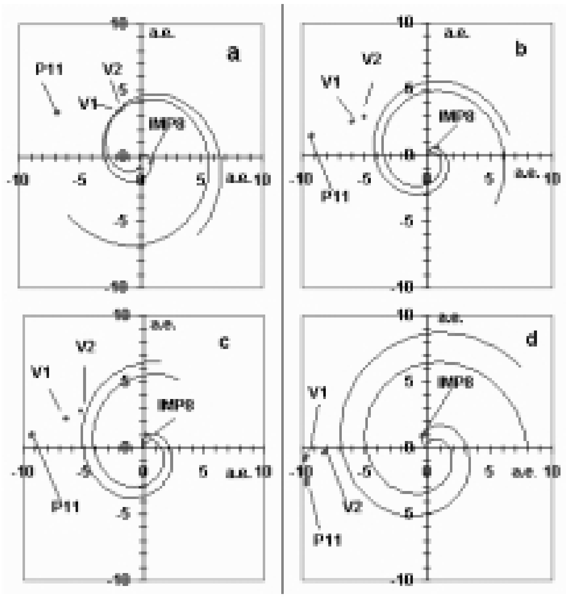

Fig. 4. Spatial structures corotating with the Sun in SE s/c coordinates projected onto the ecliptic plane. a) 22/08 – 24/09/1978; b) 29/10 – 9/11/1979; c) 6/12 – 23/2/1979; d) 5/1 – 23/1/1981.

Figure 4a illustrates a possible 'hollow' structure, which passed by IMP-8 between 22 and 24 August 1978 (period *a* in Figure 1). At this time Voyagers 1 and 2 were located near the Archimedean spiral magnetic field line passing by Earth corresponding to a solar wind speed 420 km/s as measured by IMP-8. Within 4 days the speed increased to 500 km/s and the corotating interaction region divided the spatial structure with low fluxes into two parts. The first one was detected on IMP 8 and the second on the Voyagers. As this structure corotated with the Sun it allows estimating its longitudinal extension based on its temporal duration. In this case discussed 'hollow' had an extent of ~40° in longitude at 1 AU.

During periods *b*, *c*, and *d* (see Figure 2) the flux of quiet-time low-energy protons decreased almost by an order of magnitude for more than two days. The magnetic field *B* also remained low ~5 nT. In period *d* from 5 to 8 Jan. 1981 the solar wind speed was between 415 km/s and 370 km/s (IMP-8). The same structure was observed 10 and 12 days later by Voyagers 1 and 2, respectively (Figure 4d). Therefore we suggest the existence of stable spatial structures containing low fluxes of low-energy particles similar to spiral structures slightly widening with distance

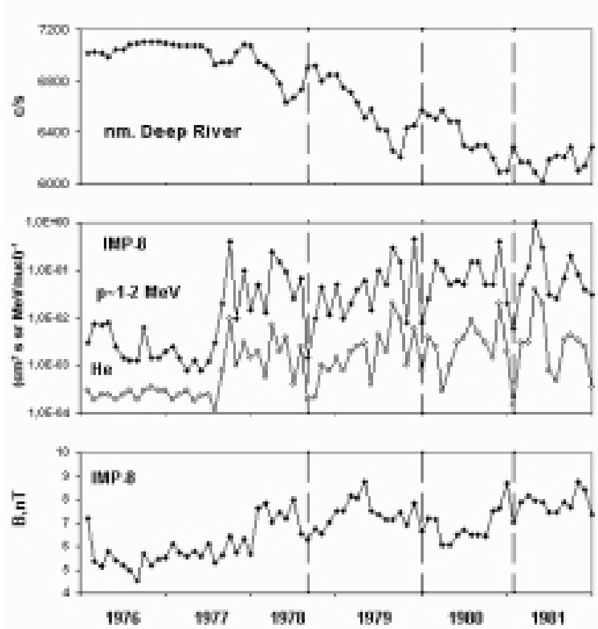

Fig. 5. Time profiles of quiet-time ~ 1 MeV proton and He fluxes, monthly average Deep River neutron monitor fluxes, and interplanetary magnetic field. Hollows are marked by vertical dashed lines.

(this may be assumed as the low-flux time intervals were more prolonged at r>1 AU than at 1 AU). The analysis of the nearly empty structures mentioned above pointed out that these hollows were bounded by Archimedean spiral field lines, had a radial spread of at least 10 AU and extended to about 60 degrees in ecliptic longitude.

At distances >10 AU interplanetary magnetic field lines become nearly azimuthal and therefore these hollows may transform into ring-like structures. Such a "ring" would spread from V2 to V1 with average solar wind velocity ~ 400 km/s which corresponds to the time lag between low-flux observations by both s/c. Figure 3 shows 3 low intensity intervals at 1 AU and later in ~17-18 days they were observed by V2. In 24, 11, 15 days after the low-fluxes were observed by V1. The first time lags correspond to time needed for these structures already existed at least for one solar rotation to corotate from IMP 8 to V2. The second series of time lags corresponds to radial moving of empty structure as a ring with solar wind velocity measured on V2.

The question arising from this discussion is that what is the nature of low-energy particles inside the 'hollows'? The values of p/He ratio are mostly low (5-25) within the hollows, matching their solar and solar wind values. Such low values of p/He may indicate that it is the 'hollow' where in the interplanetary space the contribution to quiet-time fluxes from solar flare particles is small. We have found that these empty structures appeared after steps of galactic cosmic ray modulation (Burlaga et al., 1984, 1993, 1994, and McDonald et al., 1993) simultaneously with the temporal increases of GCR. Figure 5 presents 3 steps of GCR modulation during the phase of increasing solar activity in 21 SC. In 1989-90 a prominent step have been observed (see Fig.6). Also shown are the time profiles of the minimal in month 1 MeV proton intensities. From Figures 5 and 6 one can see small temporary enhancements of neutron monitor count rates simultaneous with 'hollows'.

3 Discussion and conclusions

In spite of the effort to identify the nature of quiet-time low fluxes of MeV protons (Logachev et al., 1993, 1999, Zeldovich et al., 1995) no conclusive result has been obtained yet. Here we suggest that remnant flare particles are almost absent in the 'hollows'. It is possible that the absence of a sufficient amount of magnetic disturbances due to the abrupt temporal decrease of active processes on the Sun leads to the decrease of remnant flare particle fluxes and allow them to escape easily from the inner heliosphere thus creating these 'hollows'. This statement is confirmed by the low (5-25) values of ratio p/He inside them. Therefore it may be assumed that the 'hollow' population consists of a genuine background of quiet-time low-energy particles for current phase of the solar activity cycle. The investigation of these empty structures provides an opportunity to obtain genuine proton energy spectra during quiet Sun and to estimate radial gradient G_r at distances 1-10 AU. A preliminary estimation for 0.57-1.78 MeV protons G_r yields values between nearly zero inside ~4 AU and small negative G_r between ~4 and ~15 AU.

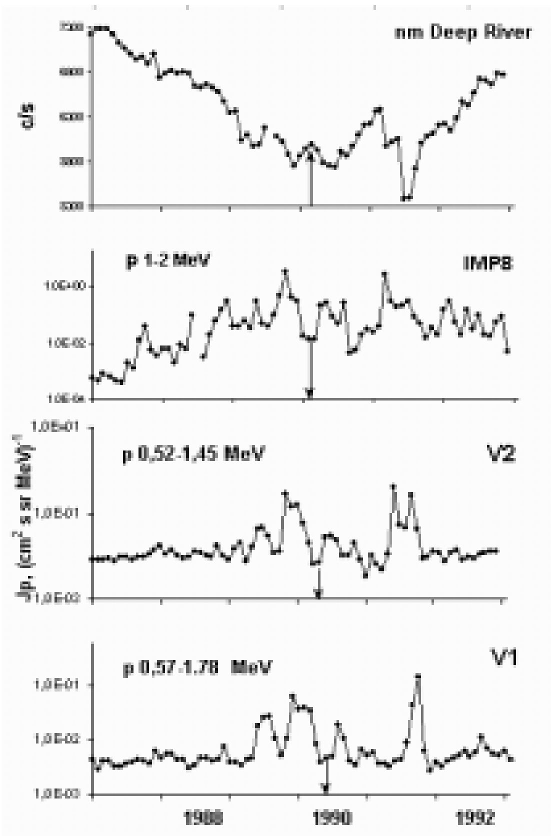

Fig. 6. A spatial structure containing low fluxes in 1990. Arrows mark large decreases of protons and increases of neutron monitor fluxes at the end of steplike modulation.

It has been pointed out (see Figure 5) that an association exists between stepwise variations of the GCR and those of the quiet-time low-energy proton fluxes (Zeldovich and Logachev, 1996). Variations of the GCR time profile are caused by the state of magnetic field in the heliosphere whereas the background fluxes of low-energy particles around ~0.5-10 AU are related to solar and interplanetary sources and depend on the time of residence of particles in the inner heliosphere. It was found that 'hollows' appeared after galactic cosmic ray modulation steps and are possibly due to decreases of solar activity. An increase in the number and power of solar sources yields, as a rule, an increase in the disturbance of the interplanetary magnetic field because of an unstable outflow of solar wind, shock occurrence, etc. These disturbances create obstacles to the low-energy particle propagation to the outer heliosphere. Therefore, high solar activity may be responsible for the observed step-like variations in the background 1 MeV proton fluxes in antiphase with similar variations of GCR.

The magnetic field inside empty spatial structures is low and characterizes the quiet interplanetary magnetic field and thereafter 'hollows' represent 1) the primary undisturbed space and the genuine background particle fluxes inside them near the minimum of the SC; 2) conditions of space and quiet-time fluxes during quiet Sun but in circumstances more disturbed than in those at minimum of the SC during other phases of solar activity cycle.

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