Enhancements of 200-2000 MeV proton intensity observed by KET/Ulysses in 1997-2005

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Abstract—**The Kiel Electron Telescope (KET) aboard the Ulysses spacecraft registers protons of near relativistic energies within the 200-2000 MeV channel. In 1997-2005 years ten enhancements above background were registered, five of which are definitely associated with ground level enhancements (GLE) of cosmic ray intensity. From the other hand, nine solar energetic particle events (SEP) accompanied by GLE did not give any particular enhancement at the Ulysses location. In order explaining these observations in different points of 3D heliosphere modulation effects of galactic cosmic ray (GCR) background as well as possible mechanisms of injection and propagation of 200-2000 MeV solar protons are discussed. Note, the KET/Ulysses registered the largest absolute enhancement within 200-2000 MeV from the solar flare of 2005 September 7, when the spacecraft was at the heliocentric distance of 4.8 AU and the solar longitude of 178^0.**

I. Introduction

Observations of 40-80 MeV solar protons in different points of the 3D heliosphere in 1997-2003 were discussed in our previous works [1-3]. According to the interpretation suggested in [1] the Sun is a source of cosmic rays prolonged in space (more than 120^0 as by latitude well as by longitude) and time (more than 9 hours). If a magnetic field line connects the observer with a source of particles, then during the rising phase (about first 30-50 hours) the observed intensity corresponds to some region of the source and large spatial gradients of SEP are observed in the interplanetary space. During the decay phase, when spatial gradients are weak or non-exist («the reservoir effect», [4]), the intensity is determined by total number of protons injected into the heliosphere and by rate of their leakage from the reservoir [1].

We found [2] the SEP events observed by Ulysses near the ecliptic at large heliocentric distances (~5 AU), when a magnetic connection between source and Ulysses was absent and solar particles propagated to a favorable field line only by the cross-field diffusion in IMF. In these cases the enhancements above background were minimal or absent, the reservoir effect was not observed. Contrary, in all events considered in [3] 40-80 MeV protons should be injected with very low and constant intensity symmetrically relatively the equator. The longitudinal dependence was not found both at high latitudes and at large heliocentric distances in the ecliptic.

In the present work we will consider for the first time observations of solar protons by the upper energy channel of KET/Ulysses within 200-2000 MeV. For such proton energies the relative enhancement above background is relatively small (less than 10 times) and analyzing SEP events one needs to account the modulation of GCR background. From one hand the energy range of 200-2000 MeV corresponds to lower energies registered by polar neutron monitors (NM), and from the other hand to the upper energy range of GOES proton detector (165-500 MeV). The GCR modulation for 1995-2001 years by using the KET/Ulysses data and observations near the Earth was investigated in [5-6], the later period of 2002-2005 would be considered here for the first time.

SEP events accompanied by GLE are distinguishable by their spectra and maximal energies, conditions of their observations by polar NM's are determined by variations of GCR background. Some features of SEP events accompanied by GLE were discussed in [7]. It was suggested in [8] that for observations of GLE the shock front accelerating SEP must cross the filed line going to the Earth and a high background is a favorable condition for their observations. According to the hypothesis of [9], the shock wave geometry is a main characteristic, which is in charge of ambiguity of SEP features observed near the Earth. Observations of relativistic solar protons in different points of the 3D heliosphere allow checking these suggestions. Moreover, it would be interesting to prove the conclusions of [1-3] for the upper energy channel.

II. Results of Observations

Figure 1 shows the intensity time profiles of 200-2000 protons (MeV KET/Ulysses) and the Oulu NM count rate. Here the Ulysses intensity is normalized to the NM count rate in 1997. Figures near peaks correspond to numbers of the Ulysses and GLE events in Table 1. Note that the Ulysses enhancement corresponding to the event of 2005 September 7 gives the vertical scale in Fig. 1. Close to the solar activity

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TABLE I

SOME CHARACTERISTICS OF RELATIVISTIC PROTON EVENTS DISCUSSED.

№	Date, day	source		№	Ulysses							GOES	
		UT	coord.	GLE	A	B	C	T1	T2	bcgd	max	bcgd	max
1	14.07.00 196d	1003	N22W07	59	3.2	N63	245	2h	12h	0.0012	0.0022	0.0011	1.2
2	15.04.01 105d	1319	S20W84	60	1.4	S14	126	3h	24h	0.0011	0.0016	0.0010	0.57
3	18.04.01 108d	0211	?W120	61	-	-	-	1h	14h	0.0013	0.0024	0.0020	0.04
4	18.06.01 169d	?	?	no	1.4	N32	70	?	2h	0.0013	0.0015	0.0013	1.5e-3
5	20.06.01 171d	?	?	no	-	-	-	?	6h	0.0013	0.0019	0.0013	-
6	15.08.01 227d	2354	?W180	no	1.6	N63	36	1h	14h	0.0013	0.0025	0.0014	0.05
7	04.11.01 308d	1603	N06W18	62	2.2	N77	65	5h	11h	0.0013	0.0017	0.0013	0.22
8	26.12.01 360d	0432	N08W54	63	2.5	N67	42	1h	5h	0.0014	0.0024	0.0012	0.09
9	28.10.03 301d	0953	S16E08	65	5.2	N06	120	17h	3h	0.0016	0.0024	0.0011	0.24
10	07.09.05 250d	1717	S06E89	no	4.8	S29	178	4h	32h	0.0021	0.0084	0.0015	0.02

Ulysses: A-heliocentric distance, B – heliographic latitude, C – solar longitude relative to the Earth; T1 – propagation time, T2 – time to maximum; background (bcgd) and maximum intensity (cm^2s ster MeV)$^{-1}$ normalized to the background of the GOES proton channel (165-500 MeV) in May-June 2001.

minimum an amplitude of GCR variations at Ulysses is considerably larger than observed by the Oulu NM. The situation has changed in 1998-1999, when a difference between energy ranges of the 200-2000 MeV channel of KET and the NM Oulu becomes important. Therefore, we use data of the GOES 165-500 MeV proton channel for comparison with Ulysses close to the solar activity maximum.

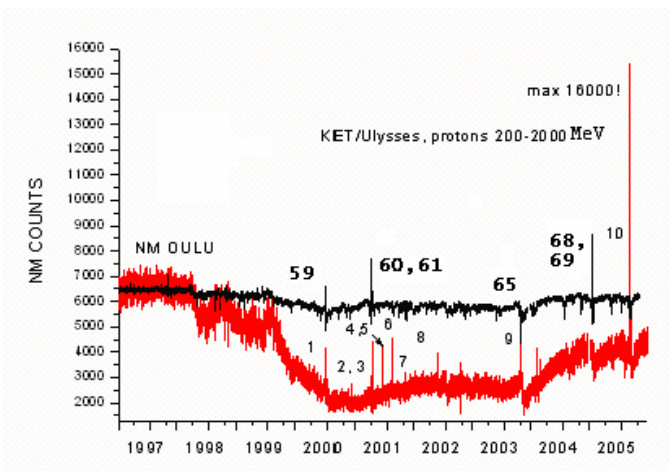

Fig. 1. Hourly average count rate of the Oulu NM (black) and the KET/Ulysses channel (red). The Ulysses data were normalized to the Oulu NM in 1997.

The count rate of the 200-2000 MeV Ulysses channel was normalized to the GOES intensity in May-June 2001, when both spacecraft were at heliocentric distances of ~1 AU in the ecliptic according to the expression

$$U_{norm} = (59 \cdot U + 5) \cdot 10^{-4} \left(cm^2 s \cdot sterMeV \right)^{-1}$$

This formulae accounts as a difference between background noises of Ulysses and GOES detectors well as the GCR radial gradient of about 2%/AU observed in the ecliptic plane in 1997 [5]. Figure 2 compares the normalized Ulysses intensities with GOES observations in logarithmic scale, the maximum intensity observed by GOES on July 14, 2000 gives the vertical scale. Absolute intensities are presented in Table 1 and Fig's 3-5.These normalization gives coinciding intensities of solar protons for the detectors on day 169 of 2001, when both spacecrafts have been located close to each other. However, this normalization is not valid for the beginning of the Ulysses mission (1990), possibly, because another type of GOES detectors at that time.

It is extremely important that here and below we use hourly average data without any smoothing. Therefore we may see effects of short term variations on long term variations.

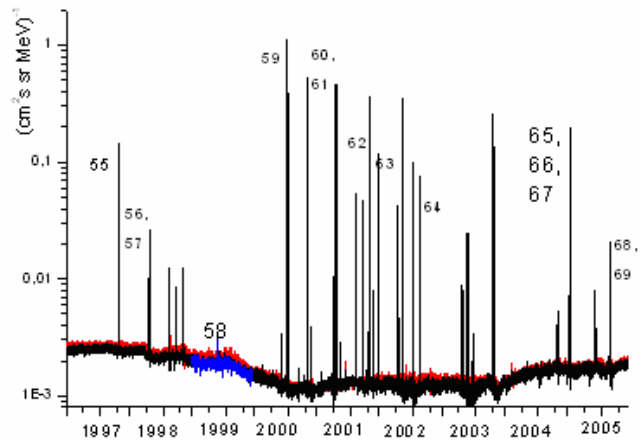

Fig. 2. Hourly average proton intensity observed by GOES (165-500 MeV, black and blue) and KET/Ulysses (200-2000 MeV, red). The Ulysses data were normalized to GOES in May-June 2001 (see the text).

III. DISCUSSION

A. *Variations of GCR Background*

Intensities of >250 MeV and >2 GeV protons measured by Ulysses were compared with IMP [5] and NM [6] data respectively. According to estimates of [5] the radial gradient of GCR was about 2.2 %/AU in 1997and increased up to 3.5%/AU in 2000, the latitudinal gradient was absent. The authors of [6] concluded that the modulation depth at high latitudes of the heliosphere is considerably larger than in the ecliptic. However spatial gradients and temporal variations were not separated in [6] for 2001-2002 .

Comparing time profiles in Fig. 3 and Fig. 5 we see that in the maximum of solar activity CR intensity is equal in different points of the heliosphere, latitudinal and radial gradients have been absent till 2002, so the modulation depth is determined by the CR intensity in the minimum of solar

activity. Considerable latitudinal and radial gradients were observed in instants of large local CR modulation near the Earth (the analogue of Forbush effect in the interplanetary space).

Note, the events of 1997, 1998 and January 2005 accompanied by GLE and registered by lower energy channels of KET/Ulysses, apparently, were not visible at such high background of GCR.

B. Proton Enhancements in the Ecliptic and Polar Latitudes

Near the ecliptic at ~1 AU we have found sharp and quick enhancements, which have been observed both at GOES and Ulysses or only at single spacecraft (lower panel, Fig. 3). For example the duration of this short event on day 169 of 2001 is about 8 hours corresponding to a longitudinal angular size of ~5^0 and a linear size of ~0.02 AU (a latitudinal size was no less then 32^0). Similar numbers give other events. Possibly, these are impulsive events, where protons have been accelerated up to energies more than 200 MeV (point and instant injection?).

Being in the ecliptic, Ulysses was in unfavorable position (~W126) for observation of the famous events on 2001 April 15 and 18, so the maximum intensities registered were much less than at the Earth. An amplitude of the April 15 event at Ulysses was smaller than of the April 18 event (vice versa at GOES), so these events give an example of the East-West effect working in the ecliptic at distances <1AU.

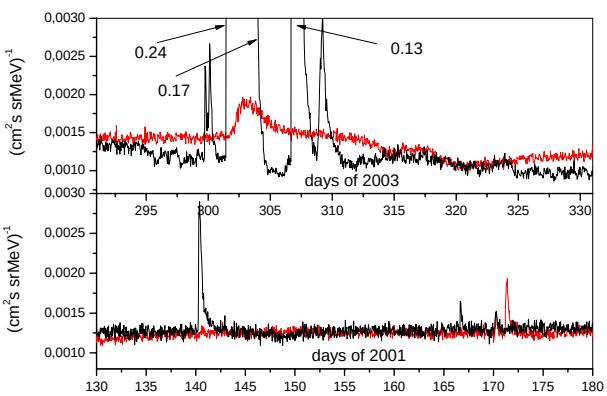

Fig. 3 The proton intensities observed by Ulysses in the ecliptic are compared with GOES observations near the Earth. The numbers indicate the GOES maximum intensity (out of scale).

Only two events were registered in the 200-2000 MeV channel of KET/Ulysses at large heliocentric distances (Fig. 4). In October-November 2003 a low level of GCR background and additional particles from, at least, two sources (GLE 65 and 66) are favorable factors (upper panel, Fig. 3). The second case of the 2005 September 7 event is outstanding considering the propagation time and the maximum intensity. Possibly previous events occurred behind the limb created special conditions for particle propagation in the heliosphere, practically without scattering along slightly curved magnetic field lines. To our opinion this is the largest proton event of the 23rd solar cycle.

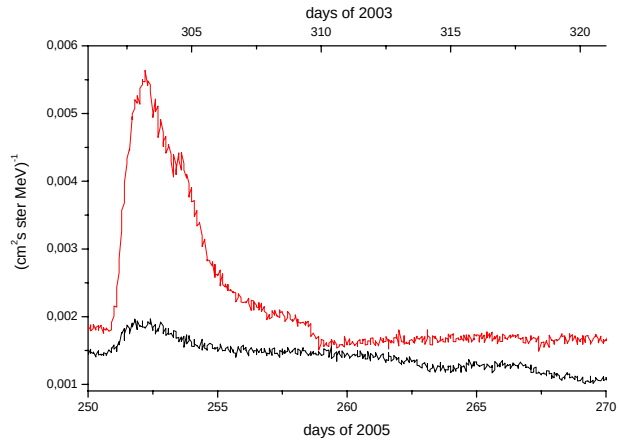

Fig. 4 Comparison of the Ulysses events in October-November 2003 (black) and September 2005 (red).

Eight events observed in the polar regions of the heliosphere for proton energies of 40-80 MeV were considered in [3]. However, only four of them show intensities above background in the 200-2000 MeV channel (Fig. 5). These are three events accompanied by GLE events and the events of 2001 August 15-16. The last event had a source behind the limb (see [10]), and might be accompanied by GLE in a case of favorable position of the Earth. Maximal intensities observed at high latitudes do not correlate with those near the Earth (Table 1), this is an evidence of direct injection of high energy protons to the polar regions. Therefore, we may conclude that events have been different only by energetic spectrum, but spatial properties of the sources and character of propagation have not changed in comparison with results obtained for lower energy protons.

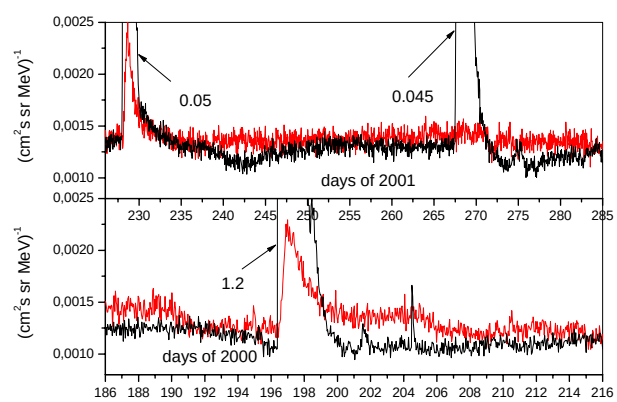

Fig. 5 The proton intensities observed by Ulysses at polar latitudes are compared with GOES observations near the Earth. The numbers indicate the GOES maximum intensity (out of scale).

IV. Conclusion

1. A depth of GCR modulation during the solar activity cycle is determined by the CR intensity in the minimum, since global latitudinal and radial have been absent in 2000-2001 years.
2. Near 1 AU were discovered very quick (small angular size) enhancements of 200-2000 MeV proton intensity (2 events), which might be considered as elementary events composing large gradual events
3. Variations of GCR background are the main factor determining a probability of 200-2000 MeV solar proton observations at large heliocentric distances.
4. The proton events at high heliolatitudes have similar characteristics, so it is unlikely that the shock wave is in charge of proton acceleration and propagation.
5. The largest proton event of the 23rd solar cycle, considering a number of protons injected into the heliosphere, occurred on 2005 September 7. The Earth was in unfavorable position for observations of solar protons.

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