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Proton acceleration during 20 January 2005 solar flare: CORONAS-F observations of high-energy γ emission and GLE

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Abstract. Solar γ emission with energy 0.05 - 300 MeV was observed by SONG instrument onboard the CORONAS-F satellite during a solar flare of 20 January 2005. Measured spectra show the peculiar excess in the 26 - 200 MeV energy range produced by neutral pion decay. The presence of pions proofs that protons were accelerated up to energies > 200 MeV during this flare. Comparison of temporal profiles of high-energy gamma emission with GLE onset time observed by neutron monitors network leads to conclusion that these protons escaped from the Sun immediately after their acceleration. The strong anisotropy of proton enhancements is discussed and a pitch angle distribution of high-energy proton fluxes in interplanetary space is estimated.

Key words: cosmic rays – GLE – magnetosphere

1. Introduction

The observations of γ-ray emissions from solar flares provide the main channel for the diagnosis of electron and ion acceleration time intervals. The importance of the measurements of solar γ rays was stressed long time ago (e.g.Chupp, 2003). A review on solar energetic particles responsible for X-ray, γ ray and neutron emissions from the Sun is presented in e.g. (Ryan, 2000). The presence of protons accelerated to > 200 MeV in the solar atmosphere is defined by the remarkable plateau in the energy range 25 - 100 MeV of the γ emission spectra produced by decay of po in the reactions with proton energy threshold of 200 - 300 MeV. Measurements of high-energy neutral emissions from the Sun since 1980 lead to few observational evidence for po decay emission during two previous solar activity cycles.

CORONAS-F satellite operates in the near-Earth circular orbit (altitude $\sim$ 500 km, inclination of 82,5°) since August 2001. The SONG instrument on board of this satellite CORONAS-F measures X-rays (0.03-0.15 MeV), γ-rays (0.15-100 MeV), neutrons (>20 MeV) electrons (11 - 108 MeV and cosmic rays (protons with the energies >70 MeV and electrons with energies >55 MeV). The detector axis is permanetly directed to the SUN. The details can be found in (Kuznetzov, 2004). SONG is a joint instrument of the Institute of Nuclear Physics, Moscow State University and Institute of Experimental Physics Slovak Academy of Sciences, Košice, Slovakia.

Four events with strong emission of high energy γ rays were observed by SONG instrument onboard the CORONAS-F satellite during the current cycle, namely solar flares of 25 August 2001, 28 October, 4 November 2003 and 20 January 2005. We present a short survey of SONG observations of intensive 20 January 2005 flare with a γ ray emission indicating a neutral pion decay spectrum shape. CORONAS-F observations of the γ-ray emission with the characteristic spectrum of π^0 decay process gave us an opportunity to compare the acceleration time of protons with Ep>200 - 300 MeV to the release time of high-energy protons measured on board Spacecraft and at ground level by the neutron monitor network. For the GLE event we illustrate the anisotropy of proton flux estimations based on computations for three neutron monitors (NM).

2. Solar and geomagnetic conditions in January 2005

Six strong solar flares of X class (in X-rays) were detected during this time interval.
The first X 1.7 started on January 1 and five others occurred between January 15 and 21. Their classes in X-rays were X1.2, X2.6, X3.8, X1-3 and X7.1, respectively. Major magnetic storms were observed on January 7 and 8 due to the arrival of transient flow from CME activity (on January 4 and 5). The >2 MeV electron fluxes at a geosynchronous orbit increased in high levels on 03-06 January (http://goes.ngdc.noaa.gov/data/plots/2005/GOES-200501.pdf). Solar activity ranged after January 14 from very low to high level. This is evident from sunspot numbers and from radio flux at 10.7 cm. The solar wind speed increases in this period over 750 km/s. The maximum solar wind speed 987 km/s was detected by ACE at 19.26 UT on January 21 (http://swdcwww.kugi.kyoto-u.ac.jp/dstdir/index.html). The Bz component of interplanetary magnetic field was negative and reached -25 nT. The >2 MeV electron fluxes at the geosynchronous orbit were at high level between 14-23 January too(http://goes. ngdc. noaa. gov/ data/plots/2005/GOES-200501.pdf). The quiet geomagnetic conditions continued from 24 till the end January.

Three magnetic storms, namely on January 7-11, 16-21 and 21-27 occurred with minimum Dst < - 100 nT. The first one, started at $\sim$ 14 UT on Janury 7 reached minimum Dst = -105 nT at 03 UT on January 8. Its recovery

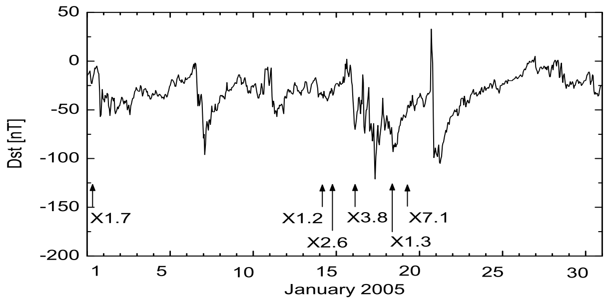

Figure 1. Dst values (http://swdcwww.kugi.kyoto-u.ac.jp/dstdir/index.html) and times of the solar flares observed during January 2005.

phase finished on January 11. The second and the third one form a "two-step" storms. The second one started at $\sim$ 22 UT on January 16 and reached its minimum Dst = -125 nT at 09UT on January 18. The third storm started on January 21 at $\sim$ 20 UT and reached minimum Dst = -113 nT on January 22 at 07 UT. Its recovery phase finished on January 27. The storms were accompanied with a dramatic redistribution of outer radiation belt electrons. In (Slivka, 2005) based on measurements from the same statellite, the position of maximum flux of electrons was shifted to much lower L values in comparison with the situation before the storms. Figure 2 (compilation from (http://swdcwww.kugi.kyoto-u.ac.jp/dstdir/index.html)) indicates the sequence of solar flares and geomagnetic activity level.

3. γ-ray emission

The X7.1/3B flare (14°N, 61°W) was observed in SXR emission from 06:00 till 11:00 UT (see upper panel of Figure 2). The sharp SXR intensity and temperature increase at 06:42:40 UT serves as an identification of the flare impulsive phase onset. This time is marked by the first dotted line. CORONAS-F observed γ emission of the flare above the low background level from the very beginning of the impulsive phase as was shown at the bottom panel of Figure 2.

The enlarged gamma ray emission time profiles for two energy channels are presented in Figure 3 (two bottom panels). The sharp increase of the high-energy gamma intensities began at 06:45:30 UT. It coincides with the second sharp increase of the temperature of a SXR source (that is marked by the second dotted vertical line in Figure 2) indicating that additional energy release leads to additional particle acceleration up to very high energies. The vertical lines in Figure 3 mark two time intervals indicating the existence at least of two distinct emission phases.

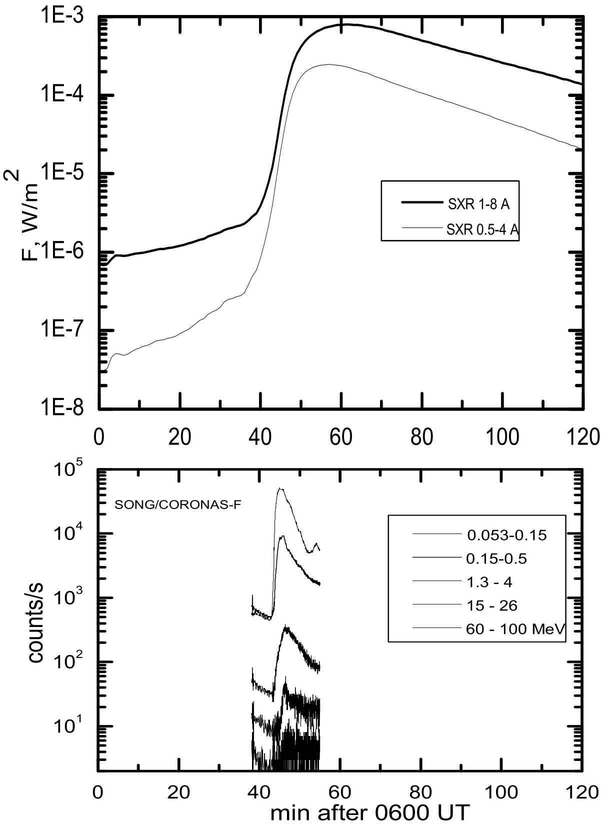

Figure 2. Upper panel: Soft X ray measurements by GOES on 20 January 20 2005. Lower panel: Excess on hard X ray and γ ray channels observed by SONG on CORONAS-F.

The spectrum shape differs significantly during these time intervals as can be seen in Figure 4.

The spectrum shape differs significantly during time intervals I versus II and III. The absence of photon fluxes $> 10^{-4}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{MeV}^{-1}$ created in the π^0 decay process during the time interval I suggests that proton energy does not reach 200 MeV or that the proton spectrum was not strong enough to create measurable photon flux near Earth. The second sharp energy release of the flare that began at 06:45:30 UT is characterized by the remarkable plateau in 25 - 100 MeV. We attribute this spectrum flattening to γ-ray spectra from π^0 decay indicating the acceleration of protons to Ep $>$ 200 MeV.

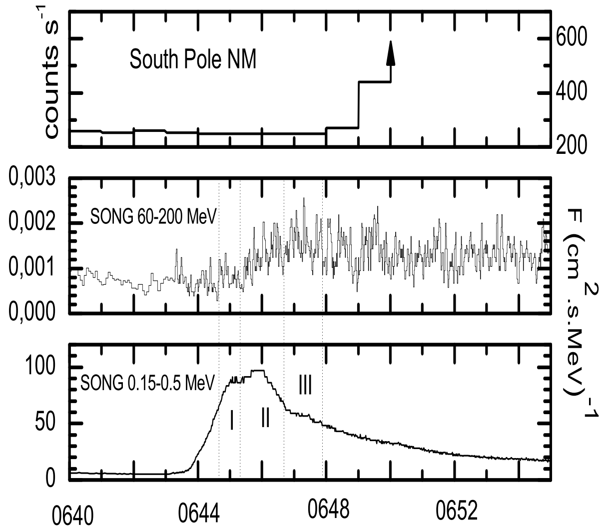

Figure 3. The temporal profile of measurements at two γ ray channels of SONG along with the onset of GLE observed on South Pole NM.

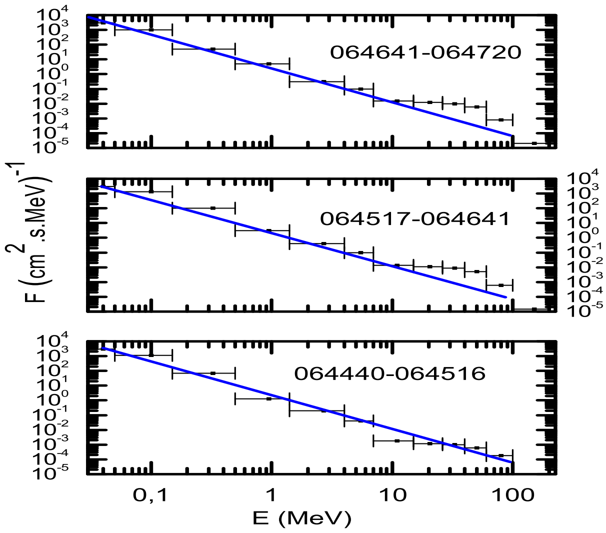

Figure 4. The energy spectra of γ rays observed by SONG during three time intervals marked in Figure 2.

4. Onset of high-energy protons measured by NM network

We have got the strong indication in γ ray observations that protons with energy > 300 MeV were accelerated on the Sun during time interval 06:38:30 - 06:42:30 ST. Solar Time (ST) refers to the UT of an event at the Sun taking into account the propagation time of γ-ray (508 s). Protons escaped from the Sun reached 1 A.U. and were detected by neutron monitor (NM) network as an event with very hard spectrum. The GLE event related to this flare was observed by several NMs in real time (Shea, 2005). The combined NM network data evidenced that protons had energies from 400 MeV (atmospheric threshold) up to several GeV and hence velocities 0.83-0.95 of the light speed c. NM Jungfraujoch (vertical cutoff rigidity R=4,6 GV) detected GLE whereas NM Athens (R=8.72 GV) did not see enhancement. The Archimedian spiral length in this day was 1.04-1.03 AU that permits to estimate the shortest propagation time for the protons propagated without scattering as 10-8.5 min. Using this propagation time value we find out that South Pole onset at 06:48:3030 s UT is consistent with the solar time interval 06:38:30-06:42:30 ST i.e. with the γ emission measured by SONG. Consequently, particle leakage from the Sun began at the moment of their acceleration without any delay. The GLE effect is highly anisotropic. Figure 5 shows the time profiles of 3 stations, namely Lomnický Štít, Oulu and Thule.

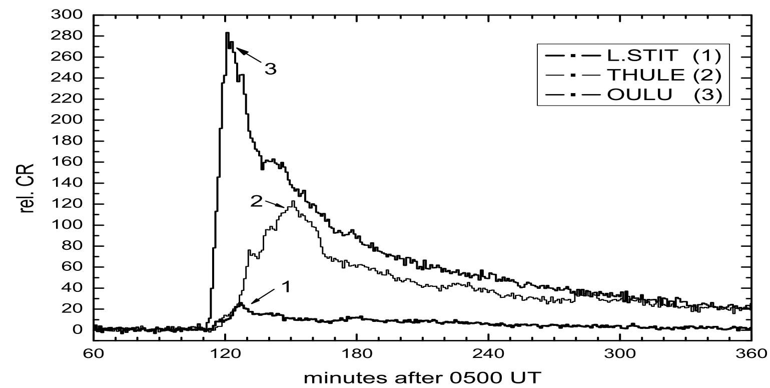

Figure 5. The neutron monitor increases during the event on 20 January 2005. Geomagnetic vertical cutoffs of Lomnický Štít (LS), Oulu and Thule are 4 GV, 0.8 GV and 0 GV respectively.

Along with the different geomagnetic cutoffs the difference in NM count rates could be attributed to the different asymptotic viewing directions. To understand at least qualitatively the difference in the NMs data with a relatively small (in comparison with the South Pole) increase and a shifted maximum to later time, we computed similarly to paper (Fedorov, 2002) the pitch angles of primary solar protons coming asymptotically from the interplanetary space. For that we used the IMF measurements and solar wind data from ACE web site and computed the asymptotic directions for the 4 stations using IGRF model and procedure (Kaššovicová, 1995). The computation results are shown in Figure 6. While Oulu and LS position yield into the predominant access of particles with pitch angles $< 100^0$ during the period of their increase, South Pole and Thule stations are predominantly collecting responses from primaries at pitch angles above 100^0 for the whole time with the increase.

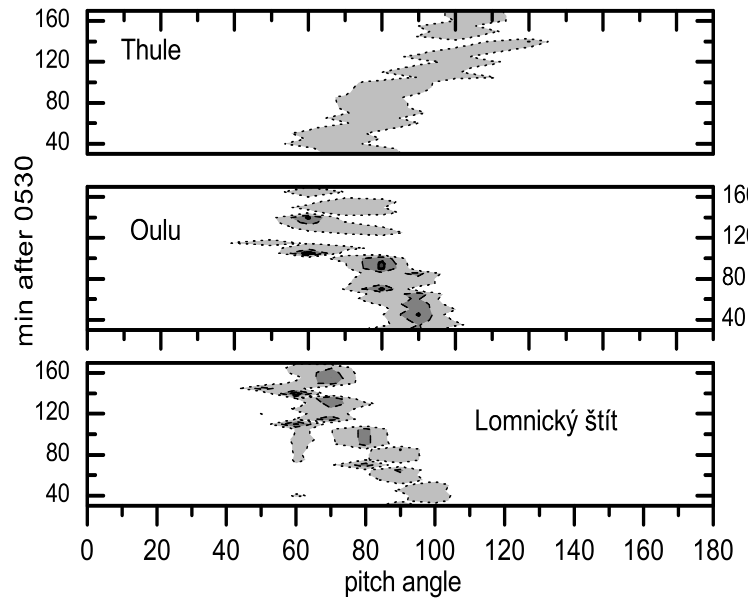

Figure 6. Contributions to the access of cosmic rays with rigidity spectra R^{-5} at 3 NMs on 20 January 2005. For each 5 min interval the computation is based on trajectory tracing (IGRF) and "measuring" the angle between IMF B (obtained from ACE web page) and the asymptotic directions. Grey code (normalized to unity in 5 min intervals) is the relative contribution to the CR access (dotted>0.2; dashed>0.4; full>0.6).

However, while pitch angles of preferential access to Thule are different from those to Oulu and LS, the difference in the time profiles of Thule (long delay of its maximum) in comparison with other two stations mentioned, is probably not only caused by difference in pitch angles. The South Pole station having also the similar course of pitch angles to Thule, has shown a considerably different time profile at the very early stage of GLE (onset at 0650 UT, Figure 3). One explanation can be a very narrow collimated flux at the first part of GLE response combined with the north-south asymmetry and/or with strong azimuthal asymmetry known e.g. from the behavior of lower energy particles near the magnetospheric boundary. Magnetic reconnection may lead to very different particles penetration inside the magnetosphere: from the day side at south and from the opposite side at north.

5. Summary

SONG experiment on CORONAS-F observed a high-energy γ-ray emission up to 300 MeV during the 20 January 2005 flare with a high time resolution. The emission is attributed to po decay implying ion acceleration at least up to 200 - 300 MeV that allowed us to trace in detail the proton time history from their "birth". Time delay calculations showed that protons with energies of 200 - 300 MeV began to escape from the Sun exactly at the time of their acceleration moving as a very narrow collimating flux at the beginning. A strong anisotropy with a signature of azimuthal asymmetry of the proton flux during the GLE is indicated.

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