Parameters of the flare and surrounding medium and their evolution during 20 January 2005 solar event

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Abstract. Basing on the data of AVS-F apparatus from SONG-D detector onboard CORONAS-F satellite, we have studied the extreme solar event of January 20, 2005 used the 2.223 MeV, 4.44 MeV and 6.13 MeV γ-lines temporal profiles. By the statistical modeling method we calculated the temporal profile of 2.223 MeV line. Calculations were performed in assumption of Bessel type of accelerated particles energy spectrum, different ³He content in the region of nuclear reactions and several density models of the solar atmosphere. Comparison of the results of modeling with observational 2.223 MeV data reveals the increasing of the ratio of ³He concentration to ¹H one during the flare from 2×10⁻⁵ at the rise phase of the gamma-ray flux up to 2×10⁻⁴ at the decay one. During the same period the spectrum became harder, spectral index changed from αT=0.005 up to 0.1, and the density of solar atmosphere increased too. Averaged over full time of 2.223 MeV γ-emission, concentration ratio of ³He/¹H is equal to (1.40±0.15)×10⁻⁴, the spectral index of accelerated protons αT=0.1 for the energy interval of 0.1-100 MeV and the density model with enlarged density up to 2×10¹⁷ cm⁻³ in the lower chromosphere and through the whole photosphere is realized. Using the AVS-F/SONG-D/CORONAS-F gamma-ray spectral data in the wide range up to 140 MeV, we have estimated the spectral index as s=2.5 in the case of power law spectrum of accelerated particles for energies more than 300 MeV.

1 Introduction

Accordingly to GOES X-ray data in the range of 0.1–8 nm, the flare of 20 January 2005 (class X7.1, ball 3B, helio-coordinates are N14, W61) began at 06:36 UT, had a maximum at 07:01 UT and finished at 07:26 UT. This flare was the most powerful in the series of January, 2005 flares and it was one of the most intensive of observed solar events [1, 2]. Bremsstrahlung from relativistic electrons and different types of nuclear narrow and broad γ-lines has been registered during the period of the flare. The nuclear lines give opportunity to receive information about ion acceleration and properties of medium. For analysis, we have used the results of AVS-F/SONG-D experiment [3-7] onboard CORONAS-F satellite [8] in wide energy range of γ-rays. Gamma-quanta with energy up to 140 MeV were observed...
by this apparatus during January 20, 2005 solar flare [5,7]. In the present work we have analyzed the temporal profile of 2.223 MeV γ-line from neutron capture by hydrogen nuclei. Previous modeling of 2.223 MeV γ-line temporal profile of this flare [9] was based on the same observational data. The modeling has demonstrated that the observed temporal profile couldn’t be appropriately described by models with usual suppositions concerning initial data of neutron production and medium properties. In the present work we have obtained the set of parameters that could describe reasonably the 2.223 MeV γ-line temporal profile.

Also we have calculated the spectral index of protons accelerated in this flare for energies more than 300 MeV in the supposition of power law spectrum using analysis of γ-emission from decay of pions.

1. The 2.223 MeV line

Previously the authors of [10] have proposed the Monte Carlo simulation method for temporal profile of 2.223 MeV line (neutron capture line) modeling, including the most important aspects of its formation. For the first time the authors of [11] have calculated the production of 2.223 MeV from instantaneous source of 0.3-100 MeV neutrons in the supposition of standard model of solar atmosphere for the quiet period. In distinction from their approach we considered different densities of the solar atmosphere [10, 12-14]. The method takes into account the initial conditions for produced in the flare neutrons, including their angular distribution, neutrons radiative capture by $^1$H, non-radiative one by $^3$He, their decay, gravitation interaction and possible escape from the Sun. Also the properties of medium in particular, γ-ray absorption in the solar atmosphere considered too. The neutron spectra in the range from 10 keV up to several GeV were calculated for some suppositions on accelerated protons in [15-16]. These spectra in the range of 0.1-100 MeV were introduced in our method. One of our parameters is the altitude density profile of the solar atmosphere (figure 1), where $H$ is the depth below the level of $10^{12}$ cm$^{-3}$. Models 2, 3, 5 present the enlarged density relative to model 1 of quiet atmosphere, model 4 characterizes the diminished one. The dependence of 2.223 MeV γ-fluxes on the model of solar atmosphere was first investigated in [10]. Later our method was extended by including flare process parameters temporal analysis [17].

![Figure 1. Models of density profile of the solar atmosphere (τ is the optical depth). Model 1 (solid line) is the combination of models HSRA [18] (for quiet period in chromosphere and partially in photosphere) and Spruit [19] (convective zone). Models 2, 3 are the combinations of higher part of model 1 and lower dashed parts. Model 5 is the combination of dashed part and two parts of model 1 (upper and lower ones).](image)

We have applied our method to the January 20, 2005 flare under supposition the stochastic particle acceleration with Bessel’s spectrum. In [20] we used four parameters of calculations: vertical density profile of the solar plasma, spectral index of particles, $^3$He content relative to $^1$H in the region of interactions, and initial angular distribution of neutrons. In figure 2 we present the comparison of the observed data and calculated ones in the supposition of three values of concentration ratio...
κ=\frac{n(^3\text{He})}{n(^1\text{H})}; “m” is number of the model of solar atmosphere density and α_T=0.1 is the spectral index of accelerated protons. Figure 2 shows the case of uniform angular distribution in the lower hemisphere of neutron ejection. We have obtained the best approximation of the temporal profile shape for each model. For this purpose the calculated curves have been stepwise linearly transformed and compared with observed ones until the least residual sum of squares (RSS) was achieved. The same calculations were made for three values of α_T, different ratios κ from $2\times10^{-5}$ up to $2\times10^{-4}$ for the most appropriated models 1 and 5. The results for the models with three parameters are presented in the table 1 in the first seven rows. The RSS method, applied to full time of 2.223 MeV emission, reveals the most acceptable set of parameters: α_T=0.1, m=5, κ=(1.40±0.15)×10^{-4} in used suppositions.

**Figure 2.** Calculated time profiles in suppositions of α_T=0.1, three values of κ for four models (a) and two models (b, c).

**Table 1.** The values of residual sum of squares for different models. In the last three rows ψ is the angle of neutrons’ direction for fan emission.

| κ (ψ) | α_T=0.005 |   | α_T=0.03 |   | α_T=0.1 |   |
|-------|------------|---|----------|---|----------|---|
|       | m=1        | m=5 | m=1        | m=5 | m=1        | m=5 |
| 2E-5  | 1.258E+05  | 2.880E+04 | 8.076E+04  | 1.991E+04 | 7.322E+04  | 1.862E+04 |
| 5E-5  | 9.419E+04  | 1.366E+04 | 5.200E+04  | 8.470E+03 | 4.702E+04  | 7.897E+03 |
| 8E-5  | 6.882E+04  | 1.159E+04 | 3.754E+04  | 5.910E+03 | 3.283E+04  | 5.264E+03 |
| 1.1E-4| 5.803E+04  | 6.482E+03 | 2.713E+04  | 4.353E+03 | 2.292E+04  | 4.110E+03 |
| 1.4E-4| 3.946E+04  | 5.035E+03 | 1.974E+04  | 3.857E+03 | 1.695E+04  | 3.779E+03 |
| 1.7E-4| 3.636E+04  | 6.687E+03 | 1.536E+04  | 5.103E+03 | 1.286E+04  | 5.007E+03 |
| 2.0E-4| 2.827E+04  | 7.329E+03 | 1.172E+04  | 6.201E+03 | 9.747E+03  | 6.155E+03 |
| 2E-5, ψ=89° | 1.881E+05 | 4.376E+04 | 1.421E+05 | 3.249E+04 | 1.331E+05 | 3.056E+04 |
| 1.1E-4, ψ=89° | 9.833E+04 | 1.504E+04 | 6.074E+04 | 9.054E+03 | 5.483E+04 | 8.286E+03 |
| 1.4E-4, ψ=89° | 7.477E+04 | 1.366E+04 | 4.532E+04 | 7.482E+03 | 4.070E+04 | 6.860E+03 |
We also considered the case of fan-shaped distribution (table 1, last three rows) corresponding to the accelerated particle movement in the magnetic field loop in the supposition of their minimal scattering on MHD-inhomogeneities [16]. Produced in nuclear reactions neutrons keep in general the direction of moving parent particles, reflected from the lower parts of magnetic loop in their Larmor movement. In this case, such far from disc centre flare, as considered one, produced neutrons and subsequent γ-quanta that pass through large grammage in their way before solar atmosphere escape may result to reducing γ-ray flux. This effect could also explain the decreasing of γ-emission intensity in the decay phase comparing with the calculations in our models. However, the results in table 1 show that in this case the least RSS takes place also in the case of a high content of $^3$He, at the same time, the agreement of calculated data with observations is worse.

2. Temporal dependence of parameters
Figure 2 and table 1 show that for some intervals of the January 20, 2005 flare 2.223 MeV temporal profile the deviations of modeling curves from data points are distinguishable, and the best coincidence at separate stage may be not the same as it was found for the averaging over the total time of γ-emission. Now we analyze this effect due investigation of the temporal evolution of density model ($m$), energy spectrum index ($\alpha_T$) of accelerated protons, and $^3$He content ($\kappa$) during the flare. For this purpose we subdivided the full time of 2.223 MeV γ-emission in three intervals. Then the observational data points in every interval were compared with the best modeling time profile for every combination of $m$, $\alpha_T$ and $\kappa$ parameters for appropriate part of total time calculated model, and the best approximation was chosen again. Figure 3 presents the final best fitting of chosen partial models. The composite model's profile allows us to make some conclusions about temporal variations of three parameters. We can see that the model of density at the first stage of γ-emission is not disturbed one and $\kappa$ is not enlarged. Model 5 is realized after $\approx 160$ s. The energy spectrum of accelerated particles becomes harder and $\kappa$ grows from $2\times10^{-5}$ up to $2.0\times10^{-4}$ during the flare.

3. The estimation of proton spectral index using pion spectrum feature
During solar flare neutral and charged pions could be produced via interactions of accelerated protons with ambient hydrogen, $\alpha$-particles and heavier nuclei. First two reaction types (see table 2) were investigated in application to solar flares since the end of 1970s – see [22-24] taking into account multiple production both of charged and neutral pions. The data of pion multiplicities at high-energy proton nuclear collisions were summarized, for example, in [25]. Also charged and neutral pions could be formed in processes of secondary neutron interactions with ambient hydrogen and heavier nucleus because of during solar flare, neutrons may be produced with energies more than pion production threshold energy via interactions of accelerated protons and heavier ions with ambient matter.

Neutral and charged pions could be formed during solar flares via the following reactions of single (reactions 1-5) and double (multiplicity M=2 in reactions 6-13) pion production (table 2). The
threshold energy of reactions with \( M>2 \) is sufficiently higher and we did not analyze it in the presented article.

### Table 2. The main reactions of pion production

| Multiplicity of pions production \( M=1 \) | Multiplicity of pions production \( M=2 \) |
|------------------------------------------|------------------------------------------|
| \( pp \rightarrow pp\pi^0 \) (1)         | \( pp \rightarrow pp\pi^0 \) (6)         |
| \( \rightarrow pp\pi^0 \)               | \( \rightarrow pp\pi^0 \)               |
| \( \rightarrow pn\pi^0 \) (2)          | \( \rightarrow pn\pi^0 \) (7)          |
| \( pn \rightarrow pn\pi^0 \) (3)       | \( pn \rightarrow pn\pi^0 \) (10)     |
| \( \rightarrow nnp\pi^0 \) (4)         | \( \rightarrow nnp\pi^0 \) (11)       |
| \( np \rightarrow np\pi^0 \) (5)       | \( np \rightarrow np\pi^0 \) (12)     |
| \( \rightarrow np\pi^0 \)              | \( \rightarrow np\pi^0 \)              |

To consider the reactions caused by interactions of accelerated protons with ambient solar matter it is possible to neglect processes (3-5) and (10-13) taking into account pion production threshold energy [24, 26] and the small ratio of produced neutrons to accelerated protons during solar flare [15]. By considering the reactions with \( pp \) in the initial state, the ratios of the numbers of pions are:

\[
P(\text{pp}) = \frac{Z}{A}.
\]

The typical value abundance of \(^4\text{He} \) relative to protons is 0.07 in ambient media and \(-0.01 \pm 0.04\) in energetic particles [24, 21], \( P(\text{pp})=0.5 \) and the relative to protons amount of produced pions is \( N(\text{pp})\sim0.07\times0.5\sim0.04 \) and the ratios of the numbers of pions in \( pp \) channels following to formula (14). Concerning interactions of accelerated \( \alpha \)-particles and ambient hydrogen, the producing of pions is possible in both \( pp \) reactions with probability (15) and \( pn \) ones with probability [27]:

\[
P(\text{np}) = (A-Z)/A
\]

For \( pn \) channels the ratios of the numbers of pions are:

\[
N_{\pi^+} : N_{\pi^0} : N_{\pi^-} = 3:4:3
\]

Taking into account the abundance of accelerated \( \alpha \)-particles, the amount of produced pions relative to protons is comparable with \( N(\text{pp}_\alpha) \) and

\[
N_{\pi^+} : N_{\pi^0} : N_{\pi^-} = 7:7:4
\]

So, the ratio of negative pions contribution to positive one is

\[
N_{\pi^-} = (4+7\times0.04) : (1+4\times0.04) \approx 3.7
\]

Neutral pions decay into two \( \gamma \)-quanta with energies of 67.6 MeV in the rest frame, and the spectrum of \( \gamma \)-emission from such decays has the broad peak shape due to the Doppler-shift with width depend from pions energy. The width of spectral feature of \( \gamma \)-emission from neutral pion decay changes from \(-100\) MeV for near pions production threshold energy of protons [22, 23, 28, 21] up to several hundreds of MeV for high energy incident protons [23, 30]. The positrons and electrons from charged pion decays formed bremsstrahlung continuum components additional to one produced by accelerated electrons. This component most easily observed at \( E_{\gamma}>10\) MeV – see, for example, [21]. The characteristic energy of point of spectral shapes switching from dominate intensity of \( \gamma \)-emission produced by bremsstrahlung of accelerated electrons and positrons from positive charged pions decays (in the first approximation it is
possible to neglect electrons formed in negative charged pions decays taking into account ratio (19)) to one from neutral pions decay depends from shape of protons spectra [22-24, 30] and it allows to make conclusion of incident protons spectrum index. Figure 4 presents the approximation of January 20, 2005 $\gamma$-emission spectrum by combination of bremsstrahlung continuum component from accelerated electrons and positrons (formed in positive charged pions decay) and the wide spectral feature caused by neutral pions decay according to power law spectral models of incident protons used in [22, 23]. The comparison of this approximation and experimental data using chi-square technique allows to conclude that model with $s=2.5$ gives the best agreement with gamma-emission spectrum registered during January 20, 2005 solar flare by AVS-F apparatus from SONG-D detector onboard CORONAS-F satellite [6, 31]. The energy of spectral shapes switching point from dominate intensity of gamma-emission produced by charged pions decays to one from neutral pion decay is $\sim 28$ MeV.

**Figure 4.** January 20, 2005 solar flare energy spectrum [9,10] (solid histogram) and the results its approximation by combination of bremsstrahlung continuum from accelerated electrons and positrons formed in positive charged pion decays (dashed line) and spectral feature caused by neutral pion decay (solid curves) for different spectral indexes of accelerated protons.

### 4. Discussion

We have shown that enlarged content of $^3$He in the solar atmosphere is one of the most probable causes of non-coincidence of 2.223 MeV temporary profile with model profile, calculated in usual suppositions of $^3$He/$^1$H=$2\times10^{-5}$, which successively used in the case of previously studied flares. We also have some other circumstances to support this cause. In the range of 15-21 MeV of $\gamma$-emission energy spectrum a faint peak was detected [5, 6]. It was observed at the 2.5 and 3 standard deviation levels at times of 06:44:52 – 06:51:16 UT and 06:47:00 – 06:49:08 UT, respectively. The authors of [31] proposed to interpret this peak as two-component $\gamma$-line, consisting of de-excitation narrow line of $15.11$ MeV from $^{12}$C de-excitations (see details in [20, 31]) and more wide radiation capture line of thermal and non-thermal neutrons by isotope $^3$He with composing $^4$He nucleus and gamma-quantum with the energy of about $20.58$ MeV:

$$n^+ + ^3\text{He} \rightarrow ^4\text{He} + \gamma.$$  \hspace{1cm} (20)

The cross-sections of both reactions are small, but the probability of the last reaction of radiative capture may increase because of enlarged content of $^3$He in the region of nuclear reactions during this solar flare or if neutron energy was $>500$ keV. In the last case the neutron capture cross-sections at $^3$He twice larger than at $^1$H - see, for example [31, 39]. In [31] it was shown that there are some other phenomena in the process of the same flare, like registration of $^3$He in the space, a faint peculiarity in RHESSI $\gamma$-ray spectral observations, that may be interpret as a line of $0.937$ MeV from the reaction...
and its registration might also confirm the conclusion of enlarged $^3$He content in the region of nuclear reactions. All these phenomena, including the direct observations of 20.58 MeV $\gamma$-line from radiative capture of neutrons by $^3$He, validate the conclusion of present study about the enlarged content of isotope $^3$He in the region of nuclear reactions during the solar flare of 20 January 2005. Additional discussion on $^3$He can be found in [20].

The specificity of 2.223 MeV line formation processes in the solar atmosphere is that accelerated protons with only limited range of energies may give the contribution to this gamma-line formation. It is well known that the range of proton energies, which participate in 2.223 MeV $\gamma$-line productions, is 0.1-100 MeV. [11-13, 32]. So, our method, based on modeling of 2.223 MeV $\gamma$-line temporal profile allows us to deduce the spectral indices in the 0.1-100 MeV range but does not allow to make any conclusions about the spectrum shape of accelerated particles in the region of relativistic energies. And, in a certain sense, the authors of [33] are right: the parameters of the spectra that have been found by this method “have no relation” to the spectra of high energy particles, accelerated in solar flares.

However, the spectral indices, estimated by our method, particularly their evolution, characterize accelerated in the flare low-energy particles on-the-scene, in its issue, that is the essential advantage of this method comparing to the measurements in the space or at the Earth by neutron monitors because of possible transformation of the fluxes in the heliosphere. Additionally note, that the spectral parameter is not an exclusive parameter, we deduce the values of four parameters of the flare and surrounding medium, which all are of interest for understanding the process of solar flare.

Concerning solar particle spectra, it should be noted, that there are created some more exact methods for finding the spectral indices of accelerated protons in different energy intervals by means of gamma emissions. They are summarized, e.g., in [34]. The accuracy of such methods in general is higher than from space measurements, or Earth surface ones, especially, in the period of large solar events, such as the flare under consideration. There are a lot of observations, confirming the complexity of magnetic conditions in the period of January 20, 2005 large solar event: magnetospheric and ionospheric storms, a large CME, changed significantly the properties of interplanetary space, the influence of preceding geomagnetic storm of the flare of January, 17 [e.g., 35, 36]. The authors of [37, 38] have observed two agglomerations of solar relativistic particles from the flare of January 20, 2005 with different character of the spectrum and with time interval between their arrival about 15-30 minutes. The analysis made in [37, 38] shows that two components have different nature: the first one with exponential spectrum well agrees with the spectrum of particles accelerated in magnetic reconnection; the second one with power law spectrum is in agreement with stochastic acceleration on plasma turbulence and likely connected to the CME.

Using all these data, including our estimated spectrum for 0.1-100 MeV and GOES-11 measurements of time profiles of several ranges in the interval of 60-300 MeV of proton energies, the authors of [33] propose to reconcile all four spectra for make some estimate of real relativistic particle spectrum. It is necessary to mark that the complexity of space conditions and their uncertainties in the period of this flare do not allow to use regular method of diffusion; uncertainties of using GOES data for spectrum estimates and using the spectra from two different nature and arrived in different time agglomerations, revealed in [37, 38], together with the using our spectrum (applicable for interval of 0.1-100 MeV only) unlikely allow to deduce the spectral index of relativistic particles correctly.

Because of the difficulties of traditional deducing the spectral index from solar cosmic rays for this event we applied the method, connected with $\gamma$-emission arisen from the pion decays. This emission gave us the possibility to reveal the spectral index of relativistic protons with $E > 300$ MeV. We have study the January 20, 2005 gamma-emission spectrum approximation by composition of continuum bremsstrahlung component from accelerated electrons and positrons formed in positive charged pion decays, and wide spectral feature caused by neutral pion decays accordingly power law spectral models of incident protons. The results of analysis allow to conclude that model with $s=2.5$ gives the best
agreement with $\gamma$-emission spectrum registered during this solar flare by AVS-F apparatus from SONG-D detector onboard CORONAS-F satellite [6, 31].

5. Conclusion
The most interesting results obtained from the study of neutron capture line during the solar event of 20 January 2005 are (i) the enhanced $^3$He content in the area of 2.223 MeV $\gamma$-line emission if averaging over the full flare duration and (ii) increasing $^3$He content, or the ratio $\kappa=n(^3\text{He})/n(^1\text{H})$, in the nuclear reactions region during the flare. Both results indirectly confirm the supposition, made in [20] about predominantly acceleration of $^3$He in this flare by the mechanism of ion–acoustic turbulence process [40] and its subsequent transfer to the lower chromosphere, for example, by means of successive pulses of thin structure of this flare, which may demonstrate multiple acceleration processes [7]. This infer is conformed with our conclusion about not enlarged value of $\kappa$ and the undisturbed character of the density model at the first stage of considered solar flare (figure 3).

In this study we also reveal the hardening of the spectrum with the time of flare and make sure again that for most part of the time of 2.223 MeV $\gamma$-line emission (periods of its maximum and its decay), the best density model of the events with gamma ray production is the model with enlarged density up to $2\times10^{17}$ cm$^{-3}$ in the lower chromosphere and photosphere.

For receive information about the spectral index of accelerated protons for energies more than 300 MeV during the flare of January 20, 2005 we have analyzed the $\gamma$-emission from decay of pions both charged and neutral. The results of investigation show that power law spectral model of incident protons with $s\approx 2.5$ gives the best agreement with the experimental data.

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