The results of January 20, 2005 solar flare study by narrow gamma lines

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Abstract. We have studied some properties of the powerful solar flare of January 20, 2005 by methods of nuclear lines analysis. The results of temporal profiles investigation in corresponding to neutron capture energy bands allow the supposition about predominant acceleration of \textsuperscript{3}He ions in the corona, their subsequent propagation to the low chromosphere and the photosphere where the area of 2.223 MeV $\gamma$-line effective productions is located. The characteristics of accelerated \textsuperscript{3}He ions propagation processes and the basic explanation of observable properties of this solar flare due to the variations of \textsuperscript{3}He content are discussed in the presented article.

1. Introduction

The characteristics of studied flare were comparable with ones of the most powerful flares in the period of the last 50 years \cite{1, 2} (see figure 1, where the proton intensities of several powerful solar events are compared).

It can be seen the proton event of January 20 is not only the most powerful, but its period of enhancement is very small. The considered event was not only one of the most powerful, but it also had some peculiarities.

Three remarkable aspects of the January 20, 2005 event are the rapid arrival of the high energy particles, their peak intensity, and the high speed of the associated coronal mass ejection \cite{2}. These characteristics might suggest that a strong shock formed very rapidly and accelerated the energetic particles. This event had the hardest spectrum observed during solar cycle 23 and also the highest \textsuperscript{\textgreater}100 MeV intensity level in $\sim$30 years, reaching its peak intensity at 1 AU within minutes. For explain the intensity profile of protons the authors of \cite{2, 3} suppose a strong shock formed very rapidly and first accelerated energetic particles traversed an extremely quiet interplanetary medium within an interplanetary coronal mass ejection that originated less than 2 days earlier in the same active region as the January 20 event. Such a situation leads to good magnetic connection and minimal scattering.

Extreme solar event of 20 January 2005 was observed in the period of anomalously high flare activity of the Sun in the phase of deep decay of the solar cycle. We study this unusual event in more details. Its characteristics are as follows (see, for example, \cite{1-5}):

- Class: X7.1/3B;
- Location: N14W61;
- Begin-peak-end: 06:36UT-07:01 UT-07:26 UT.
- Accompaniment events: CME, Proton event, GLE (ground level event)
- Strong gamma-ray emissions: bremsstrahlung, nuclear narrow + broad lines
Figure 1. The January 20, 2005 flare: the event reached peak intensity on RHESSI data much faster than any of the largest SEP events of the past 30 years. Adopted from [3].

Figure 2. Models of altitude density profile of solar atmosphere ($\tau$ is optical depth). 1 and 5 are adopted from [4].

2. January 20, 2005 event as $^3$He-reach flare

We have analyzed the data on gamma-emission registered from the AVS-F apparatus onboard CORONAS-F satellite (detector SONG-D) [5, 7] together with the data of RHESSI satellite [6].

The foundation of our modeling are statistical (Monte-Carlo) calculations of every neutron-hydrogen elastic collision in the way of neutron from the solar atmosphere density of $\sim 10^{12}$ cm$^{-3}$ (the region of neutron production) downwards to the low chromosphere and photosphere. Notice, that the region of ion acceleration is usually accepted to be at higher levels, with densities of $\sim 10^{11}$ cm$^{-3}$. Neutrons lose their energy, become in thermal ones, and then neutrons begin to effectively assimilate by protons of solar lower chromosphere and photosphere, producing $\gamma$-line with 2.223 MeV energy of quantum.

In the present work we have analyze the time profile of 2.223 MeV $\gamma$-line from neutron captures by hydrogen nuclei, we also use narrow de-excitation gamma lines from $^{12}$C at 4.44 MeV and $^{16}$O at 6.13. We have made Monte-Carlo simulation of processes with energetic neutrons (details see, for instance [4, 8-10]).

Table 1. The sums of square deviations in the pairs of observable - fit points

| $^3$He/H | $\alpha T=0.03$ | $\alpha T=0.1$ |
|----------|---------------|---------------|
|          | $m=1$         | $m=5$         | $m=1$         | $m=5$         |
| $^3$He/H=2$\times10^{-5}$ | 8.076E+04 | 1.991E+04 | 7.322E+04 | 1.862E+04 |
| $^3$He/H=5$\times10^{-5}$ | 5.200E+04 | 8.470E+03 | 4.702E+04 | 7.897E+03 |
| $^3$He/H=8$\times10^{-5}$ | 3.754E+04 | 5.910E+03 | 3.283E+04 | 5.264E+03 |
| $^3$He/H=1.1$\times10^{-4}$ | 2.713E+04 | 4.353E+03 | 2.292E+04 | 4.110E+03 |
| $^3$He/H=1.4$\times10^{-4}$ | 1.974E+04 | 3.857E+03 | 1.695E+04 | 3.779E+03 |
| $^3$He/H=1.7$\times10^{-4}$ | 1.536E+04 | 5.103E+03 | 1.286E+04 | 5.007E+03 |
| $^3$He/H=2.0$\times10^{-4}$ | 1.172E+04 | 6.201E+03 | 9.747E+03 | 6.155E+03 |

Large quantity of flare parameters gives us possibility to determine some of them using the rational choice of data subsequence research. Using the time profile of this flare in energy band corresponding the neutron capture line of 2.223 MeV we have study the density of the region of neutron interactions and the content of $^3$He in this area. Besides, we estimate spectral index of accelerated particles $\alpha T$ in the case of Bessel spectrum or power-law index $s$ in the case of power-law spectrum. Thus, we have 3...
parameters for calculations (and in one case we add one additional parameter: geometry of neutron escape): 1) the model of altitude profile of solar atmosphere; 2) \( \kappa = n(^{3}\text{He})/n(^{1}\text{H}) \); 3) \( \alpha T \) in the supposition of Bessel spectrum. Five models of altitude density profile of solar atmosphere usually considered. Model 1 (solid line) is the combined one of models HSRA [10] of quiet atmosphere (in chromosphere and partially in photosphere) and [11] (convective zone). Models 2, 3 are combined of higher part of model 1 and higher dashed parts. Model 5 presents the enhanced density in the most part of depths interval under consideration. In our study we used in the calculations only models 1 and 5 - see figure 2 [4, 8]. Model 5 is a specially selected form best describes the vertical profile of the density of the solar atmosphere during flares and is combined of dashed part and two parts of model 1.

![Figure 3](image_url)

**Figure 3.** Calculated time profiles in suppositions of different combinations of \( \kappa, \alpha T, \) and \( m \) and its comparision with data observed by from the AVS-F apparatus onboard CORONAS-F satellite (detector SONG-D).

Modeling technique of such flares, for example, was developed in [8, 9, 12, 13]. Now we apply our method to the flare under consideration. At the figures 3 (a, b) we present the comparison of the observable data and calculated ones in the supposition of usual average concentration ratio \( \kappa = n(^{3}\text{He})/n(^{1}\text{H}) = 2 \times 10^{-5} \), \( m \) is number of the solar atmosphere density model and \( \alpha T \) is accelerated ions spectral index. Preliminary consideration of this case was done in [8]. Figures show the graphs of models with uniform angular distribution in the lower hemisphere of neutron ejection. Calculated curves were linearly transformed until the square deviations from observable data minimal sums will be achieved. Then the resulting curves calculated in different suppositions, may be compared each with others. The same approximations, but with enhanced content of \(^{3}\text{He} \) are presented in the figure 3 (panels d, e, f and g) for the most character and distinguishable models 1 and 5. The least square sums of the models with 3 parameters are presented in the table 1, where \( m \) is density model, \( \alpha T \) – spectral index of accelerated particles, \( \kappa = n(^{3}\text{He})/n(^{1}\text{H}) \). The method of the least square sums, applied to full time of 2.223 MeV emission, reveals the most acceptable set of parameters: \( \alpha T = 0.1 \), \( m = 5 \), \( \kappa = (1.4 \pm 0.15) \times 10^{-4} \) for used suppositions.
3. Conclusion
In this work we have revealed the enlarged $^3\text{He}/\text{H}$ ratio in the area of 2.223 MeV $\gamma$-line formation for January 20, 2005 solar flare and investigate this flare parameters evolutions with time. It is shown that a satisfactory flare approximation cannot be achieved by normally observed isotope $^3\text{He}$ abundance in the flare region where $\kappa = 2 \times 10^{-5}$. The several parameters of the solar flare January 20, 2005 were found by the least-squares method in suggestion of a stochastic acceleration mechanism. The calculations of all possible combinations of parameter values $\alpha_T$, $m$, $\kappa$ (concentrations relation) were carried out as assuming constant flare averaged set of parameters as for ones that change over time. Assuming constant in time parameters, the best match with observations was obtained by the following flare parameters set: $\alpha_T = 0.1$, $m = 1$, $\kappa = (1.40 \pm 0.15) \times 10^{-4}$.

The best results of temporary profile modeling of this flare can be achieved when approval of flare’s parameters temporal evolution. Thus, during the flare the spectral index of accelerated particles increases from $\alpha_T = 0.005$ to 0.1, i.e. the spectrum of particles is hardened, the abundance of $^3\text{He}$ in relation to hydrogen (i.e. the value $\kappa = ^3\text{He}/\text{H}$) grows and density described by unperturbed atmosphere model 1 on growth phase of flare since 0 to 170 s, evolves to "flare model" $m = 5$ on the decay phase in the time interval 170-850 s. This result allows to conclude slowing of $\kappa = ^3\text{He}/\text{H}$ growth during flare decay phase and acceleration of $^3\text{He}$ ions in the area of other particles acceleration during this solar event.

We have shown the enlarged content of the $^3\text{He}/\text{H}$ ratio in the area of 2.223 MeV productions is connected with predominant acceleration of $^3\text{He}$ ions in the area of acceleration in the coronal or high chromospheric layers. Also we conclude that enlarged content of $^3\text{He}$ 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 $^3\text{He}/\text{H}=2\times10^{-5}$, which successively used in the case of previously studied flares. But we have to note that there are some other circumstances to support the enlarged $^3\text{He}$ content mentioned in the section 1 and at the Figure 3. All these phenomena, including the direct observations of 20.58 MeV $\gamma$-line from radiative capture of neutrons by $^3\text{He}$ [14], validate the conclusion of present study about the enlarged content of isotope $^3\text{He}$ in the region of nuclear reactions during the solar flare of 20 January 2005.

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