32ND INTERNATIONAL COSMIC RAY CONFERENCE, BEIJING 2011

Study of 20 January 2005 solar flare area by certain gamma-ray lines

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DOI: 10.7529/ICRC2011/V10/0702

Abstract: Basing on the AVS-F apparatus data of SONG-D detector onboard CORONAS-F satellite on definite gamma-ray lines, we study the extreme solar event of 20 January 2005. By the statistical modeling method we calculate the 2.223 MeV γ-line time profile. The calculations have been performed in assumption of the Bessel type of accelerated particles energy spectrum, different ^{3}He content in the nuclear reactions region and several density models of the solar atmosphere. A comparison the results of modeling with observable data reveals the increasing of ^{3}He content in relation to ^{1}H with the time of flare duration from the small level of 2×10^{-5} at the phase of increasing of the gamma-ray flux up to 2×10^{-4} at the decay phase. In the same period the spectral index αT of protons has increased (the spectrum became harder) and the density of solar atmosphere has increased too. When averaging over full time of 2.223 MeV γ-emission, the ratio ^{3}He/^{1}H=$(1.4\pm0.15)\times10^{-4}$, the spectral index of protons energy αT is rather close to 0.1 (a rough estimation), and the density model with enlarged density up to 2×10^{17} см$^{-3}$ in the lower chromosphere and in whole thickness of the photosphere is realized.

Keywords: solar flare, nuclear interaction gamma-ray lines, neutrons, ^{3}He content, density model

1 Introduction

Extreme solar event of 20 January 2005 was observed in the period of anomalously high flare activity of the Sun in January 2005 in the phase of deep decay of the solar cycle. According 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. The origin of this event was NOAA 10720 active area. This flare was the most powerful in the series of January, 2005 flares and it was one of the most powerful of observable event [1]. There were also coronal ejection (CME), powerful proton event and great GLE (Ground Level Event) during this flare [2].

Bremsstrahlung from electrons and different types of nuclear narrow and broad γ-ray lines have been observable 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 apparatus [4-8] in CORONAS-F experiment [3], in wide energy range of γ-rays. γ-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 analyze the temporal profile of 2.223 MeV γ-line from neutron captures by hydrogen nuclei. Previous modeling 2.223 MeV γ-line time profile of this flare [9] was based on the observational data of AVS-F [5, 8] from SONG-D from CORONAS-F. The modeling has demonstrated that the observable temporal profile couldn't be appropriately described by modeling with usual suppositions concerning initial data of neutron production and medium properties. In the present work we try to find out the set of parameters that could describe reasonably the time profile.

2 2.223 MeV line

Previously the authors of [10] have proposed the Monte Carlo simulation method for time profile of 2.223 MeV line (neutron capture line) modeling, including the most important aspects of its formation. The method takes in account the initial conditions of neutrons produced in the flare, neutron radiative and non-radiative captures, their decay and possible escape from the Sun, gravitation and properties of medium. One of the used parameters is the altitude density profile of the solar atmosphere – see figure 1. 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 [11]. Later our method was extended by including temporal analysis of the process parameters [12].

Now we apply our method to the flare under consideration. To usually parameters (vertical density profile of the solar plasma and spectral index of accelerated particles) we add two more parameters: ^{3}He content relative to ^{1}H in the region of interactions and initial angular distribution of neutrons. At the figures 2(a,b,c) we present the comparison of the observable data and calculated ones in the supposition of usual average concentration ratio $\kappa = n(^3\mathrm{He})/n(\mathrm{H}) = 2\times10^{-5}$, "*m*" is number of the model of solar atmosphere density and αT is spectral index of accelerated ions. Preliminary consideration of this case was done in [9]. Figures give the graphs of models and uniform angular distribution in the lower hemisphere of neutron ejection. Calculated curves were linearly transformed until the least square 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}He are presented in the figure 2(d, e, f) and 2(g, h, i) 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 in the first 7 lines, αT – spectral index of accelerated particles, $\kappa = n(^3\mathrm{He})/n(\mathrm{H})$. The method of the least square sums, applied to full time of 2.223 MeV emission, reveals the most acceptable set of parameters: αT=0.1, *m*=5, $\kappa = (1.4\pm0.15)\times10^{-4}$ for used suppositions.

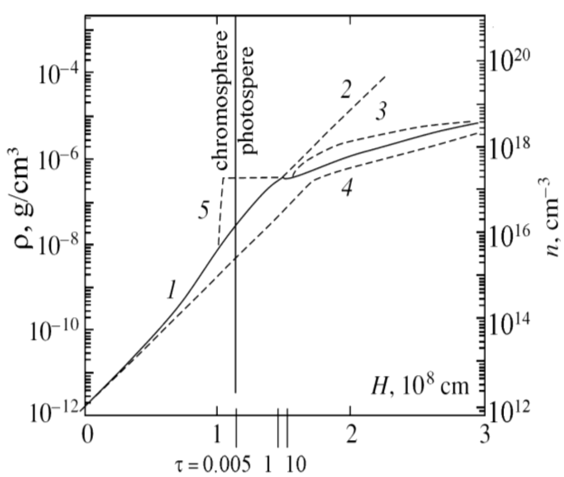

Figure 1. Models of density profile of the solar atmosphere. τ is optical depth. Model 1 (solid line) is the combined one of models HSRA (in chromosphere and partially in photosphere) and Spruit (convective zone). Models 2, 3 are combined of higher part of model 1 and lower dashed parts. Model 5 is combined of dashed part and two parts of model 1.

We also consider the case of fan-shaped distribution (Table 1, last three lines) corresponding to the accelerated particle movement in the magnetic field loop in the supposition of their minimal scattering on MHD-inhomogenuities [13]. Produced in nuclear reactions neutrons keep in general the direction of moving parent particles, which reflected from the lower parts of magnetic loop in their Larmor movement. Such far from disc center flare, as considered, may produce neutrons and then gamma-quanta that pass through large grammage. This effect could also explain the lack of gamma-emission comparing with the calculations in our models. Nevertheless, the results in Table 2 show that in this case the minimum of the least square sums is achieved together with enhanced content of ^{3}He too, and the agreement with data is worse.

Figures 2(a-i) show that for some intervals of 2.223 MeV time profile the deviations of modeling curves from data points are noticeable, 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. For analyzing this effect we also investigated the temporal dependence of 2.223 MeV flux on density model (*m)*, energy spectrum index (αT) of accelerated ions, and ^{3}He content (κ). For this purpose we subdivided the full time of 2.223 MeV in three intervals. Then the observational data points in every interval was compared with the best modeling time profile for every combination of *m*, αT and κ parameters for appropriate part of total time calculated model, then the best fit was chosen. Figure 3 gives the best composition of chosen partial models. The composite model's profile lets us 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 κ is not enlarged. The energy spectrum of accelerated particles is hardening with the time.

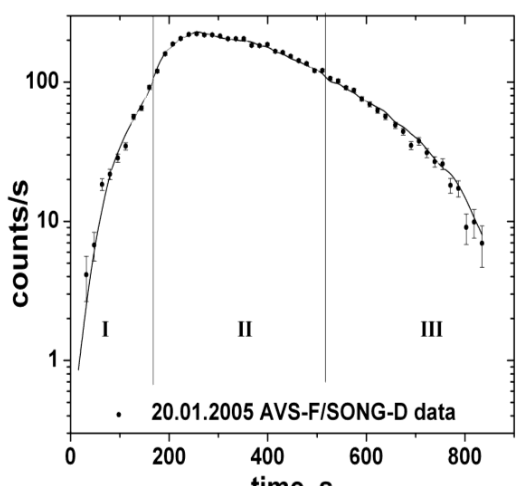

Figure 3. The best approximation of observational data by combined model. The best meanings of parameters for separate intervals are $\kappa=2\times10^{-5}$, αT=0.005, m=1 - for I; $\kappa=1.4\times10^{-4}$, αT=0.03, m=5 - for II; $\kappa=2.0\times10^{-4}$, αT=0.1, m=5 - for III.

3 Discussion

In the range of 15-21 MeV of γ-emission energy spectrum a faint peak was detected [7, 5]. The authors of [14] proposed to interpret this peak as two-component γ-line, consisting of de-excitation narrow line of 15.11 MeV from ^{12}C de-excitation and more wide radiation capture line of thermal neutrons by isotope ^{3}He with composing ^{4}He nucleus and gamma-quantum with the minimal energy of about 20.58 MeV. 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. The authors of [14] gave two estimates of ^{3}He content: $\kappa > 1\times10^{-4}$ (from preliminary calculations) and $\kappa<1.54\times10^{-4}$ (from measurements of energetic particles and solar wind in the period of 20 January 2005 solar event near the Earth) (see [14] and references there). Deduced in the present work meaning $\kappa=(1.4\pm0.15)\times10^{-4}$ is in agreement with these limitations. Our method is independent of calculating method [14], which has used the reaction of non-radiative capture of neutrons by ^{3}He. So, it may be considered as an additional confirmation of enlarged $n(^{3}He)/n(H)$ ratio and consequently as an indirect confirmation of ^{3}He contribution to γ-emission in the range of 15-21 MeV.

4 Conclusion

The investigation of 20 January 2005 solar flare shows that our model 5 with the enhanced density in the lower chromosphere and photosphere begins to realize only after ≈160 s from the beginning of 2.223 MeV γ -emission. At the preceding, first stage the quiet, non-disturbed atmosphere is more plausible. We also have found out the hardening of accelerated particles spectrum with the time. Previously, we had made the similar conclusions for the solar flares of 16 December 1988 and 28 October 2003 [12, 9] in the supposition of ^{3}He content of $\kappa=2\times10^{-5}$. In the present work the content of ^{3}He is found to enlarge during the period of γ -emission from 2×10^{-5} at the rise phase up to 2.0×10^{-4} at the decay phase. In reality, the solar events with predominant acceleration of ^{3}He ions comparing with ^{4}He and, as a result, ^{3}He enrichment are well known. Accelerated ^{3}He ions may move in different directions, and they may penetrate into dense layers, where they affect on 2.223 MeV line production and produce the 20.58 MeV faint broad line.

Acknowledgements

The authors are very indebted to Dr. V.T. Voronchev for a consultation on the reactions of radiative capture between nucleons and light nuclei. This work has been supported partly by the Russian Foundation of Basic Research (grant 08-02-92208).

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αT=0.005		αT=0.03		αT=0.1	
m=1	m=5	m=1	m=5	m=1	m=5
^{3}He/H=2E-5					
1.258E+05	2.880E+04	8.076E+04	1.991E+04	7.322E+04	1.862E+04
^{3}He/H=5E-5					
9.419E+04	1.366E+04	5.200E+04	8.470E+03	4.702E+04	7.897E+03
^{3}He/H=8E-5					
6.882E+04	1.159E+04	3.754E+04	5.910E+03	3.283E+04	5.264E+03
^{3}He/H=1.1E-4					
5.803E+04	6.482E+03	2.713E+04	4.353E+03	2.292E+04	4.110E+03
^{3}He/H=1.4E-4					
3.946E+04	5.035E+03	1.974E+04	3.857E+03	1.695E+04	3.779E+03
^{3}He/H=1.7E-4					
3.636E+04	6.687E+03	1.536E+04	5.103E+03	1.286E+04	5.007E+03
^{3}He/H=2.0E-4					
2.827E+04	7.329E+03	1.172E+04	6.201E+03	9.747E+03	6.155E+03
^{3}He/H=2E-5, ψ=89°					
1.881E+05	4.376E+04	1.421E+05	3.249E+04	1.331E+05	3.056E+04
^{3}He/H=1.1E-4, ψ=89°					
9.833E+04	1.504E+04	6.074E+04	9.054E+03	5.483E+04	8.286E+03
^{3}He/H=1.4E-4, ψ=89°					
7.477E+04	1.366E+04	4.532E+04	7.482E+03	4.070E+04	6.860E+03

Table 1. Least square sums deviations models of observational data. In the last 3 lines ψ is the angle of neutron movement for fan emission.

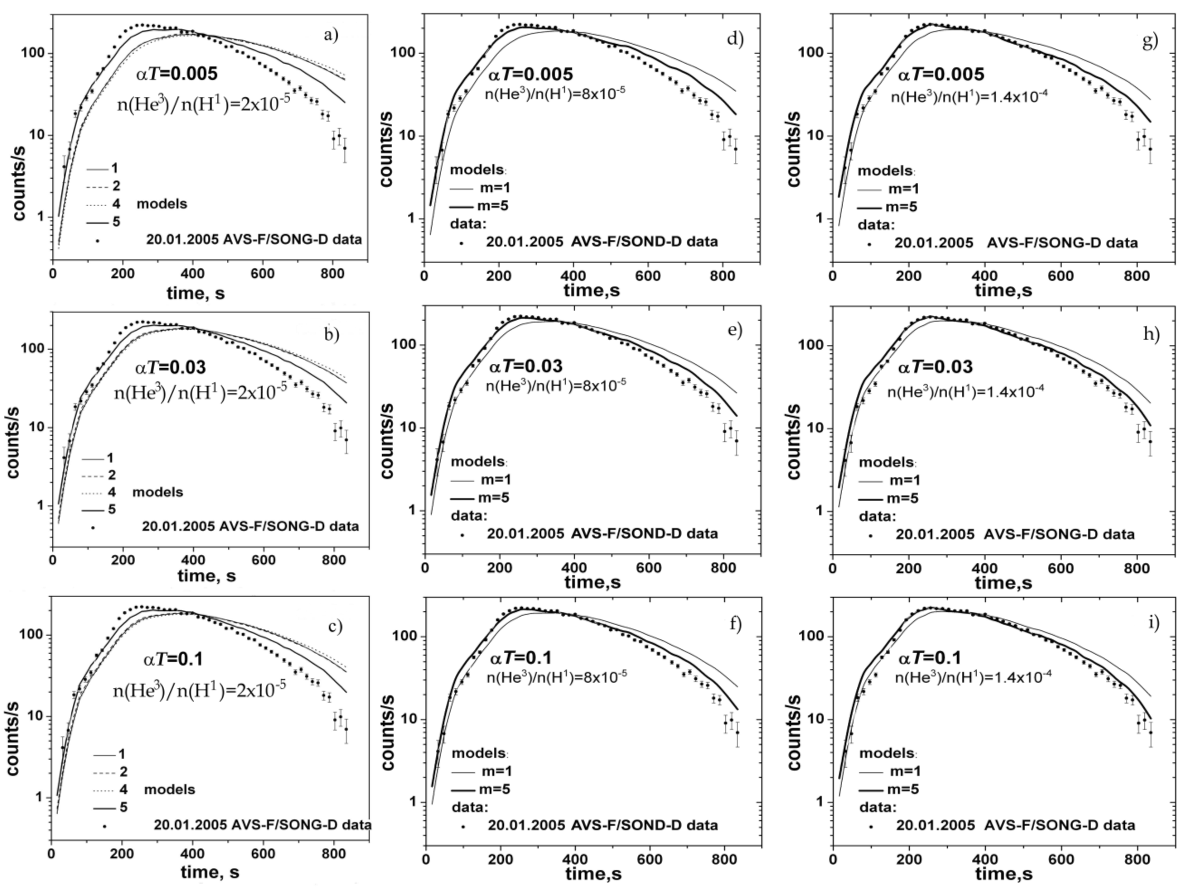

Figure 2. Calculated time profiles in suppositions of combinations of κ, αT, and m