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Study of the 28 October 2003 solar flare by means of 2.223 MeV gamma-emission

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Abstract: We have studied some characteristics of the 28 October 2003 powerful solar flare and surrounding medium by means of 2.223 MeV line time profile of gamma-emission. The modeling of time history and comparing it with the observational data reveals the considerable enhancement of the solar atmosphere density in the deep photospheric layers during the decay phase of gamma emission. Besides, the analysis let us detect the hardening of a neutron spectrum in the decay phase comparing to the rising one.

Introduction

The neutron capture line of 2.223 MeV from solar flares has been analyzed directly or by using additional data to obtain the characteristics of particle acceleration in solar flares and properties of surrounding solar atmosphere. In particular, Ramaty and Murphy [1] used the fluences of 2.223 MeV line, for determining the energy spectra of solar energetic particles, Hua and Lingenfelter [2] studied their angular distributions and production of secondary neutrons, and Yoshimori et al. [3] investigated photospheric ^{3}He abundance.

The other authors [e.g. 4, 5] have developed an approach to determine the most probable profile of plasma density in the solar photosphere and adjoining levels during the period of a flare. By the 2.223 MeV line data on three large flares, 22 March 1991 [6], 6 November 1997 [5] and 16 December 1988 [7] the plausible model of the solar atmosphere density in the period of flare and some evidence of the effect of density enhancement was obtained. Gan [8, 9] was the first who applied the time profiles of calculated partial fluences of neutron capture line φ(2.223 MeV) and annihilation line φ(0.511 MeV) to deduce the spectral evolution of accelerated charged particles. Similar studies have been recently carried out for the RHESSI flare of 23 July 2002 [10].

In [2, 11] the energy spectra of solar flare neutrons were calculated in different suppositions on accelerated particle spectra. Founding on these neutron spectra, in the case of the flare 16 December 1988 the authors [7] deduced additionally the character of accelerated particles energy spectrum evolution.

In the present work we apply the developed approach to the powerful solar event of 28 October 2003.

Method

The calculations of neutron propagation in the solar matter and 2.223 MeV line production are carried out using Monte-Carlo simulation, with due account for the models of vertical density profile of the solar plasma. For our SINP code we make allowance for: (1) neutron deceleration in elastic collisions with hydrogen nuclei, with due account for the energy and angular dependencies of cross-sections for *np*-scattering; (2) possible energetic neutron escape from the Sun; (3) gravitational neutron-Sun interaction; (4) thermal motion of decelerated neutrons; (5) neutron decay; (6) neutron captures by hydrogen ^{1}H, with the production of deuterium ^{2}H and gamma-quantum of 2.223 MeV; (7) non-radiative neutron absorption on ^{3}He; (8) gamma-ray absorption in the solar atmosphere in dependence on solar flare central angle; (9) time profile of initial neutron production; (10) initial neutron spectra, and (11) altitude dependence of surrounding matter density. The relative abundance of ^{3}He/^{1}H is taken as 2×10^{-5} e.g., [2, 3]. The time history of initial neutron production is assumed to be analogous (similar) to that of total fluence of ^{12}C+^{16}O nuclear deexcitation lines in the range of 4.1-6.4 MeV. Calculations are made with SINP code for neutrons with energies of 1-100 MeV that are the most important ones for the 2.223 MeV line production. The primary neutrons are assumed to be emitted isotropically in the lower half-space (towards the Sun) from the levels with densities less than 5×10^{15} cm^{-3}. As a basic density model (BDM) (m=1) we have used the standard astrophysical model HSRA (Harvard-Smithsonian Reference Atmosphere) for the lower chromosphere and quiet photosphere [13] together with a model of convection zone [14] consistent with the first one.

To determine possible deviations of the model, realizing in the observable flare from the BDM, we have also composed four additional models (m=2, 3, 4, 5) representing smaller and larger densities at photospheric and adjoining levels as compared with the standard model (m=1) of the quiet Sun (Table 1), see also e.g. [4]. In more detail, our method and calculation model (SINP code) are described elsewhere (see, *e.g.*, [7].

Table 1: Characteristics of models. m is the number of model. Parameter τ is the optical depth for a wavelength of 500 nm, the level τ = 0.005 corresponds to the top of the photosphere.

№, m	Character of density	
	Brief	Detailed
1	The main astrophysical model of the lower chromosphere and photosphere HSRA [7] together with the model of convective zone of Spruit [1]	Grows gradually from $1.5\cdot10^{16}$ cm^{-3} at the top of photosphere up to $2\cdot10^{17}$ cm^{-3} at the 330 km level lower, where τ=1 and sharply grows up to τ=10 in the depth of 60 km.
2	Enhanced into and under the photosphere	Enhanced to $8\cdot10^{17}$ cm^{-3} at the depth ~500 км under the top of photosphere.
3	Enhanced into and under the photosphere	Grows up more slowly under the photosphere and mounts to $6\cdot10^{17}$ cm^{-3} at the same depth.
4	Depressed from the low chromospere down to the lower levels	Reduction of the density from the low chromospere down to the deep layers. The density is $3\cdot10^{15}$ cm^{-3} at the top of photosphere and $2\cdot10^{16}$ cm^{-3}.at the 330 km lower level.
5	Enhanced in the whole thickness of the photosprere.	The density is $2\cdot10^{17}$ cm^{-3} through the complete thickness of the photosphere.

Results

The flare of 28 October 2003 began at 9:41 UT, had its maximum at 11:10 and ended about 11:24 UT. It lasted about 15 min in the gamma-ray band. It appeared in the NOAA active region 10486. We apply our method to investigate the 28 October 2003 solar flare of X17.2/4B importance with coordinates S16E08 [12] and present the results for this powerful and long-duration flare. The data on 2.223 MeV and summarized fluxes of 4.44 and 6.13 MeV gamma emission from INTEGRAL are used [15].

The calculations of time profiles of gamma fluxes were made in supposition of Bessel form (stochastic acceleration) of accelerated particles energy spectrum for three meanings of spectral parameter αT: 0.005, 0.03 and 0.1 (Fig.1).

Table 2: The least square sums (Σ)

αT	model	Σ
0.005	1	5.1031E+02
	2	5.3191E+02
	3	5.5098E+02
	4	6.3365E+02
	5	1.3819E+02
0.03	1	2.5450E+02
	2	2.3119E+02
	3	2.4751E+02
	4	2.9343E+02
	5	1.3002E+02
0.1	1	2.2200E+02
	2	1.9599E+02
	3	2.1556E+02
	4	2.5121E+02
	5	1.3227E+02

Analysis

The table 1 shows that the best modeling time profile is in the case of αT=0.03 and m=5. This means the density enhancement in the whole thickness of photosphere. We can also conclude from the Fig. 1 that m=5 begins to realize at about 400th s. Another conclusion is that the better fitting in the rising phase is αT=0.005 and in the phases of maximum and decay the best fitting is αT=0.1

Conclusion

In the present work we confirm the previously conclusions about the density enhancements in the deep photospheric or subphotospheric layers that were made for 3 flares. The hardening of particle spectra is also confirmed.
Since the character of 2.223 MeV gamma-emission time history depends mainly on the accelerated particles energy spectrum, density of surrounding atmosphere, content of ^{3}He in the solar atmosphere and angular distribution of accelerated particles, it would be useful to have methods to reveal the portion of separate

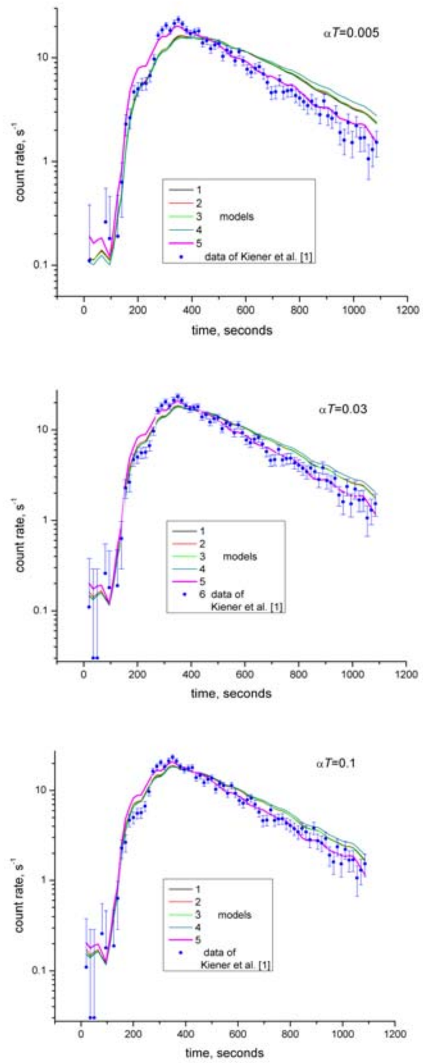

Figure 1: Observational data of 2.223 MeV gamma-emission and modeling with spectral indexes 0.005, 0.03 and 0.1 for five models.

the components. The possible registration of the gamma-line at 20.58 MeV arising from radiative absorption neutrons on ^{3}He may be use in this way.

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