About models of solar atmosphere density vertical profile

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The study of active processes in outer levels of the Sun requires the using information about physical conditions in these external layers, or suppositions about the model of solar atmospheric levels and processes in them. The main characteristics of the nuclear processes are density and chemical and isotopic composition. In different cases, this list may include temperature, pressure, and other parameters. The method of study flares, using neutrons, suppose the knowledge or suppositions about density vertical profile of surrounding medium and chemical and isotopic composition of the region of acceleration and lower regions – chromosphere and photosphere. Our studies are founded on nuclear methods, particularly, gamma-emissions from acceleration processes and nuclear reactions. Initially we used the standard density models. Later we also composed new models for find the best ones for describe the processes in the flares. We present a short survey of the solar atmosphere density vertical profile models. We also include in the survey the development of our method, completed in our own works and in the works of other researchers.

Method of calculation of the 2.223 MeV line temporal profile proposed in SINP MSU

Some time ago we have shown that the plasma density distribution in the solar atmosphere and photosphere effects on the fluxes of secondary neutrons in the media and consequently, on the altitude distribution of thermalized neutrons during a flare (see, for example, Kuzhevskij et al., 1998, 2005). As a result, the 2.223 MeV line time profiles may be used to determine the most probable character of altitude density profile in the solar photosphere and adjoining levels during the period of a certain flare.

During the onset and development of a flare, and also in the post-flare stage, fluctuations of the plasma density and temperature should unavoidably appear in the solar atmosphere on various spatial and temporal scales (Somov et al., 1979, Baranovskii, 1989, Gan et al, 1991, Boiko and Livshits, 1995, Somov and Bogachev, 2003). These theoretical works analyzing the response of the solar atmosphere to the primary energy release of a flare indicate that the motion of a cool, dense condensation (or several such condensations) ahead of the shock wave propagating downwards from the region of energy release (i.e., toward the photosphere) is possible, that is confirmed, for example, by the data for the white flares of June 4, 1980 and June 15, 1991 (Babin and Koval, 1999). In the latter case, a radial velocity for the downward motion of the radiating material of 20–23 km/s was obtained for a chromospheric condensation formed during the sudden heating of the upper chromosphere by the flux of heat from the corona. It is likely that the presence of downward moving radiating material is a common feature of the impulsive phases of powerful flares (Babin and Koval, 1999). On the other hand, we have the concept of a new magnetic field ascending in a previously existing region of “old” field. Such rising magnetic fields are considered to be sources of flares, as has been confirmed by observations – see, for example, Ishkov, 1998.

The neutrons arising during interactions between accelerated particles and various nuclei are decelerated in the solar atmosphere and, when they reach thermal energies, begin to be efficiently captured by hydrogen nuclei ^1H, leading to the formation of deuterium ^2H (or d) and gamma-quanta with energy E_γ = 2.223 MeV:

$$n + {}^1H \rightarrow d + \gamma. \qquad (1)$$

But reaction of the non-radiative capture of a neutron by a ^3He nucleus has substantially larger cross-section that reaction (1) and for this reason flux density of 2.223 MeV line depends on abundance of ^3He too – see next section of this chapter. Neutrons are not only efficiently captured by ^3He nuclei, but also decay over a mean lifetime of $\tau_d \approx 880.1 \pm 1.1$ s. In addition, neutrons can be scattered into large angles, with their subsequent escape into interplanetary space. All these factors decrease the number of neutrons that are captured by hydrogen, thereby decreasing the emergent flux of gamma-rays with Eγ = 2.223 MeV.

In this part of chapter we briefly describe the proposed in SINP MSU method and computational model that we have used for modeling of 2.223 MeV line temporal profile.

The previous model computations of (Kuzhevskij and Troitskaia, 1989) for the case of an instantaneous point source of neutrons identified the main factors influencing the distribution of depths at which neutrons of various energies are thermalized:

1. energy spectrum of neutrons,
2. angular characteristics of the incident beam,
3. angular dependence for the elastic scattering of neutrons on hydrogen,
4. density profile with height in the solar atmosphere,
5. kinematics of the nuclear reactions involved.

The most important conclusion of this early work was the dependence of the character of thermalized neutron distribution on the character of the solar atmosphere. This conclusion leads to the consequence about the dependence of 2.223 MeV gamma-line time profile on the altitude density model distribution.

For the first time the idea of such approach was suggested in 1986 (see Kuzhevskij and Troitskaia, 1995) and it was firstly applied to the solar flare γ-emission analysis in (Kuzhevskij et al, 1991). On this basis, a method for deriving the density profile with height in the solar atmosphere during a flare using the observed time variations of the flux of gamma-rays with Eγ = 2.223 MeV was proposed. The review of complete method presented in (Kuzhevskij et al, 2005b).

Kuzhevskij and Kogan-Laskina, 1990 obtained analytical expressions based on decay time constant analysis of gamma-ray radiation due to neutron absorption on hydrogen. The results was used to study relative changing of solar plasma density.

The SINP-code method based on Monte-Carlo simulations has been developed in a series of works (Kuzhevskij et al, 1998, Kuzhevskij and Troitskaia, 2001, Kuzhevskij et al, 2001, Kuzhevskij et al,, 2002, Troitskaia et al, 2003, Troitskaia et al, 2005) (as a review see Kuzhevskij et al, 2005b). The method provides the character of density model and numerical data on it.

Computations were carried out for (monoenergetic) neutrons with energies in the range En = 0.1– 100 MeV, which were the most efficient in producing gamma-rays with Eγ = 2.223 MeV. The isotropic emission of neutrons into a lower hemisphere from a level lying above the photosphere with a number density of no more than 5×10^{15} cm^{-3} was assumed, since only near this depth neutrons with minimum initial energies of En = 0, 1 MeV become thermalized (the zero depth corresponds to the level with number density 10^{12} cm^{-3}). Analogous computations were carried out for the case when the initial energy spectrum of the neutrons was a power law $(E_n)^s$ with index s changed from 0 to 3, for various density profiles with height in the solar atmosphere. The duration and time profile of the flux of emitted primary neutrons were also taken into account, as well as their non-radiative absorption by ^3He nuclei. The dependence of the flux of gamma-rays with Eγ = 2.223 MeV on the central (heliocentric) angle of the flare was studied separately.

The illustration of models you may see in the presentation №343 (Figure 1).

Models describing the density of the solar atmosphere as a function of depth: solid curve (1) is standard HSRA–Spruit model (Gingerich et al., 1971, Spruit, 1974), curves (2)–(5) presents the deformed models of Kuzhevskij and Troitskaia, 1989 (their deviations from model 1 are shown by the dashed curves). τ is the optical depth to radiation with wavelength λ = 500 nm. Adopted from Kuzhevskij et al, 2005b.

To allow for possible deviations of the density from the standard model of quiet Sun, for the unperturbed solar atmosphere (model 1; i.e., m = 1, with m also denoting the model number), Kuzhevskij et al.,1998 constructed four additional models corresponding to both enhanced and lowered densities in layers at various depths - see Figure 4. In the basic model 1, the density grows smoothly from 1.5×10^{16} cm^{-3} at the top of the photosphere (where the optical depth to radiation at wavelength of 5000 Å is τ = 0.005) to 2.5×10^{17} cm^{-3} at a level 330 km lower, where τ = 1; over the following 60 km in depth, the optical depth grows to τ = 10. In the model number 2, the density increases to 8×10^{17} cm^{-3} at depths of about 500 km below the top of the photosphere, i.e., in deep subphotospheric layers; in the model 3, the density grows smoothly below the photosphere, reaching 6×10^{17} cm^{-3} at the same depths. Model 4 represents the case of decreased density, with the reduction beginning above the photosphere, and the density taking the value 3×10^{15} cm^{-3} at the top of the photosphere and 2×10^{16} cm^{-3} 330 km below this level. Model 5 corresponds to the special case of an enhanced density equal to 2.5 × 1017 cm−3 over the entire thickness of the photosphere. The height dependence for the density and temperature of the solar atmosphere in the quiet Sun model (curve 1 in the Figure 4) corresponds to the model for the lower chromosphere and photosphere (Gingerich et al, 1991), which is in agreement with the model for the convective zone (Spruit, 1977).

The main processes in the region of solar flare and the most significant properties of medium

The medium in (Kuzhevskij and Troitskaia, 1989) was taken to be pure hydrogen but with a small amount of 3He, namely the ratio of 3He/H = 2×10-5 in numbers of nuclei (the case of 20 January, 2005 see below, section 4), and the computations were carried out for an instantaneous point source of neutrons (Kuzhevskij and Troitskaia, 1989, Kuzhevskij et al, 1991, Kuzhevskij et al, 1998) and the five density models presented in the Figure 4. Kuzhevskij and Troitskaia, 2001 took into account the contribution of non-radiative absorption of neutrons by 3He nuclei. The computations of (Kuzhevskij and Troitskaia, 2001, Kuzhevskij et al, 1991, Kuzhevskij et al, 1996) included the duration and time profile for the injection of neutrons, which were taken into account using the method proposed earlier in (Kuzhevskij et al, 1998). The initial angular distribution of the neutrons was taken to be isotropic. In fact, it proved to be sufficient to consider neutrons only in the lower hemisphere. Other important aspects of the problem were subsequently studied, for instance, two possible types of particle acceleration during a flare (stochastic and acceleration on shock waves) new data on neutron producing reactions (Hua et al., 2002). Finally, we showed that it is important to take into account the following processes if we wish to make effective use of data for 2.223 MeV gamma-ray radiation:

1. the deceleration of neutrons in the solar atmosphere due to elastic scattering on hydrogen nuclei, taking into account the energy and angular dependences of the effective cross sections for np scattering,
2. possible escape of energetic neutrons with energies En ≥ 2 keV from the solar atmosphere,
3. gravitational action of the Sun on neutrons with En < 2 keV,
4. thermal motions of decelerated neutrons,
5. neutron decay,
6. captures of neutrons by hydrogen, with the formation of a deuteron and a gamma-ray with energyMeV,
7. non-radiative capture of neutrons by 3He nuclei,
8. absorption of emergent gamma-rays as a function of the position of a flare on the Sun relative to the observer (the central angle of the flare),
9. the time profile for the injection of neutrons under the assumption that it is proportional to the profile for the injection of the total flux of gamma-ray radiation with energies 4–7 MeV corresponding to the excitation of nuclei of 12C and 16O,
10. initial spectrum of the neutrons,
11. dependence of the density of the surrounding medium on height.

Later the dependence of the flux of gamma-rays on the central angle of the flare (Kuzhevskij and Troitskaia, 2001), more accurate account of the non-radiative capture of neutrons by 3He nuclei (Kuzhevskij et al, 2001) were include in model computations, and the direct inclusion of the original spectra of accelerated particles via neutron spectra, calculated by Hua and Lingenfelter, 1987 and Hua et al., 2002 was done. We have to note that we use only limited quantity of parameter meanings of both types of spectra: αT =0.005, 0.03, 0.1 for Bessel type and s=2, 4, 6 for power-low spectrum, so we have opportunity only to estimate the spectral parameter, and, that is more important, to find a trend of spectrum hardening or softening with time.

The results of analysis allow making conclusion that, in many cases, differences in the time profiles of the 2.223 MeV line due to properties of the density models for the solar atmosphere can be observed using these existing detectors. A number of studies show that the density of solar plasma during the flare is not described by the standard astrophysical model of quiet Sun. There are also some theoretical models analyzing the solar atmosphere response to the flare initial energy release. These models are postulating downwards mass movement in the form of one of a few relatively cold dense condensations before a shock wave moving downwards from the region of energy release (e.g., Somov and Bogachev, 2003). This picture is confirmed, for example, by the data for the white flares of 4 June 1980 and 15 June 1991 (Babin et al., 1999).

In this part of chapter we discuss 2.223 MeV line flux temporal profile of the solar flare December 16, 1988. This event (class X4.7/2B) occurred at a heliocentric angle of 43◦ in the active region AR5278 (N27, E33). The SMM gamma-ray spectrometer began to record the flare at 08:28:50 UT (Vestrand et al. 1999, Rieger, 1996) and its total duration was 3 555 s. The temporal profile of the gamma-ray emission at 2.223 MeV had four peaks (Vestrand et al., 1987, Gan, 1998). To compare our model calculations with observations, we used the most intensive third peak which was observed between 08:54:46 and 09:01:03 UT.

Energy spectrum of accelerated solar protons was assumed to have a power-law form with a spectral index s = 4. Figure 5a presents our best approximation. It corresponds to the case of model 5 with the density enhancement in the thickness of the solar photosphere. The approximations for the rest four models are also plotted.

The using SINP method requires experimental data with sufficient statistic and temporal resolution. Early data of INTEGRAL (Kiener et al, 2006), SMM/GRS (Vestrand et al, 1999), AVS-F/CORONAS-F (see, for example Arkhangelskaja et al 2008, 2008a, 2009, 2009a) etc. were used for SINP method applications for temporal profiles investigation. Now we using databases of RHESSI (Gan, 2005), GBM/Fermi (http://hesperia.gsfc.nasa.gov/fermi_solar/) and other satellite observing solar emission. In the future sufficient data quality will obtained from solar oriented part of GAMMA-400 lateral aperture (Arkhangelskaja et al 2015, 2016, Topchiev 2016).

We also studied a set of other combinations of parameters αT and power-law indexes s with corresponding models at different positions (levels) of the neutron source (Troitskaia et al., 2007), and our main result (model 5) remains valid. The authors (Troitskaia et al., 2007) used the new energy spectra of secondary neutrons calculated in (Hua et al., 2002) with new data on neutron production cross-sections and new kinematics of the process. These new calculations took into account anisotropic neutron emission produced in the solar flare magnetic loop models. We also investigated the case when energy spectrum of accelerated solar protons was assumed to have a Bessel function form with a characteristic spectral parameter αT = 0.03. Figure 5b presents our best approximation. Again, it corresponds to the case of model 5 with the density enhancement in the thickness of the photosphere.

At the Figure 5c results of this flare temporal profile detailed analysis in the 3 time intervals: the growth phase (t1); t2 and t3 on the decay phase are shown. But for growth phase of temporal profile the best fit is m=1 with αT = 0.1 (fit m=5, αT = 0.03 (Figure 5b) has smaller significance level and the larger least square deviation sum correspondingly- -see (Troitskaia et al., 2003, Kuzhevskij et al, 2005b) and for the decay phase the best fit is m = 5, αT = 0.005 and m = 5, αT = 0.1 for intervals t2 and t3 correspondingly. Thus, we conclude that significant density enhancement appeared in the decay phase ~140 s after the onset of the growth phase.

Other example is the October 28, 2003 solar event, which 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 (Veselovskiy et al, 2004) 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 (Kiener et al, 2006). 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 ofspectral parameter α*T*: 0.005, 0.03 and 0.1 (see Figure.6). Analysis of calculations

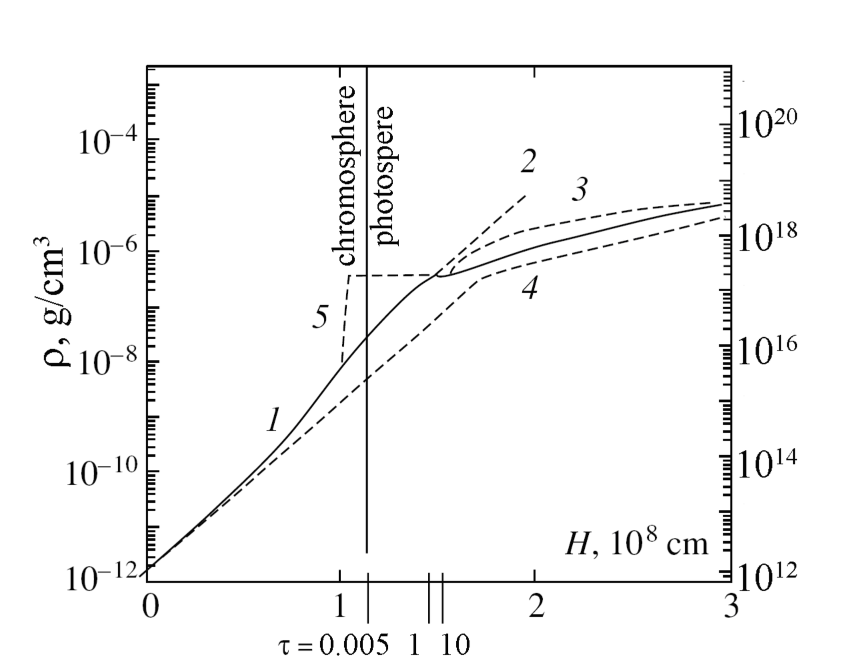

Fig.1. Model 1 was composed of model HSRA or Model Gingerich et. al, composed with model of photospheric and lower layers (model of Spruit). It was founded on optical lines data. Other models (2-5) were composed with using gamma ray experimental data.

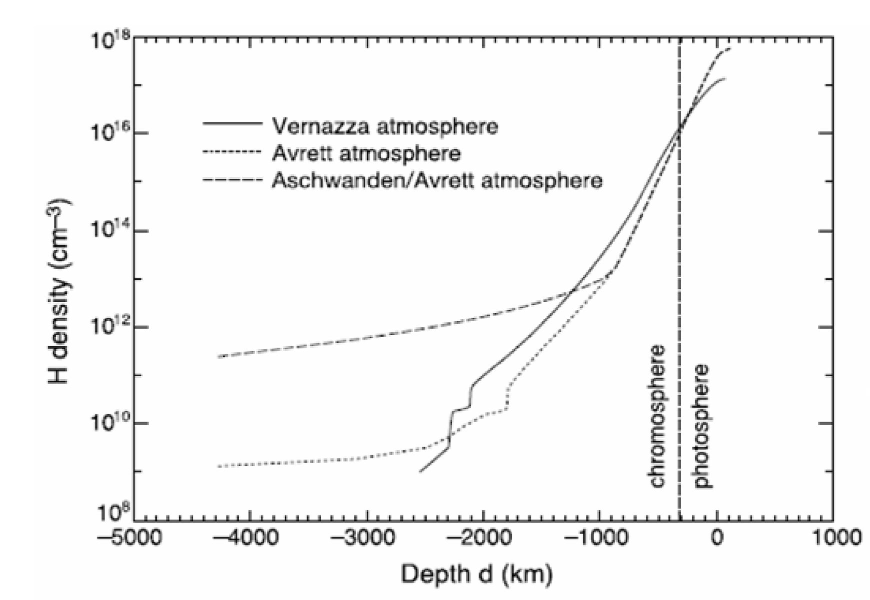

Fig.2. Ashwanden model was model was founded on x-ray data. Complex model of Ashwanden/Avrett atmosphere was applied to the solar flare in [8] Share G., Murphy R.J., Smith D. et al.

shows that the best modeling time profile is in the case of α*T*=0.03 and *m*=5. This means the density enhancement in the whole thickness of photosphere. We can also conclude from the Figure.6 that *m*=5 begins to realize at about 180th s from the flare g-emission onset. Another conclusion is that the better fitting in the rising phase is α*T*=0.005 and in the phases of maximum and decay the best fitting is α*T*=0.1

Our analysis have shown that usually the spectrum of protons to evolve with time during flare and density enhancements in the deep layers of the photosphere occurs for some investigated flares: November 6, 1997, March 22, 1991, and December 16, 1988 and October 28, 2003 (Kuzhevskij et al, 2005, Miroshnichenko et al, 2006, Troitskaya et al, 2009, Troitskaya et al, 2010). By the presence of such enhancements, it is possible to explain the shape of temporal profile of the solar flare gamma-emission in the 2.223 MeV line. Thus, we suggest that density enhancements in the deep layers of the photosphere may be rather common feature for powerful solar flares on the whole.

For two flares (December 16, 1988 and October 28, 2003) the results of 2.223 MeV gamma-emission temporal profile analysis allow to make conclusion that the proton spectrum became harder with time of the flare (αT grows from 0.005 to 0.1) – in the case of December 16, 1988 αT grows in the decay phase from its beginning to the end, and in the case of October 28, 2003 αT grows from the rising phase to decay one.

The authors of (Kuzhevskij et al., 1996a, 1996b, 1998) were the first who investigated the line 2.223 MeV time profile dependence on the altitude density model of the solar atmosphere.

In the most part of the investigated flares (with calculations over whole time of gamma-emission or over the separate time intervals) our 5-th model of the solar atmosphere density or the model with the enhancement in photosphere and lowest chromosphere (see Fig.1) successfully describes the time profile of γ-emission with energy 2.223 MeV. Note that this model is based on gamma-ray studies in contrary to optically based and X- ray based models. Now we may confirm that our density model firstly proposed in (Kuzhevskij et al., 1996a, 1996b) is the most appropriate one to describe and explicate the processes in solar flares with gamma- emission.

2.223 MeV line temporal profile and the abundance of 3He

The line 2.223 MeV depends on the 3He content because the considerable portion of neutrons may be absorbed by 3He in the process of non-radiative capture with very high cross-section. Particularly, the temporal profile of this line fluence is sensible to the content of 3He. So, we may consider the self-consistent task for finding 3He content or, at least, limitation for its abundance during the flare. Together with this, the possibility of determining the 3He content in the photosphere from observations of gamma-ray lines was demonstrated (Ramaty et al, 1987, Hua. and Lingenfelter, 1987, Gan, 2002). Gamma-ray data for flares were applied to the development of techniques for solar nuclear gamma-ray spectroscopy, which can be used to determine the elementary composition of particles in the places where nuclear reactions occur, as well as the composition of the accelerated particles taking part in these reactions (Ramaty et al, 1975, Murphy et al, 1991).

As it was mentioned above, the main source of gamma-rays with energy Eγ = 2.223 MeV is reaction of neutron capture by hydrogen nuclei 1H. However, the flux density of these gamma-rays depends strongly on the number density of 3He nuclei in the solar atmosphere (Lingenfelter, 1969, Wang and Ramaty, 1974) because of neutrons also can be non-radiative captured by a 3He nucleus, with the formation of tritium 3H:

$$n + {}^3He \rightarrow {}^3H + p \qquad (2)$$

The cross section for this reaction is nearly a factor of 1.7 × 104 higher than the cross section for neutron capture by hydrogen. Data on the density of 3He in the Sun imply that the roles of these two reactions should be comparable (Kuzhevskij, 1982).

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References

Arkhangelskaja, I.V., Kotov, Yu.D., Arkhangelsky, A.I., et al. *Proc. of the International Symposium SEE 2007: Fundamental Science and Applied Aspects;* Mavromichalaki, H. and Papaioannou A.; Eds.; National & Kapodistrian University of Athens: Athens, Greece, 2008; pp. 123-126.

Arkhangelskaja, I.V., Arkhangelsky, A.I., Glyanenko, A.S., et al. *Proc. of the International Symposium SEE 2007: Fundamental Science and Applied Aspects;* Mavromichalaki, H., Papaioannou, A.;Eds.; National & Kapodistrian University of Athens: Athens, Greece, 2008a; pp. 178-181.

Arkhangelskaja I.V., Kotov Yu.D., Arkhangelsky A.I., et al. *Adv. Space Res*. 2009, *43*, 542-546. Arkhangelskaja, I.V., Arkhangelsky, A.I., Kotov, Yu.D., et al. *Adv. Space Res*. 2009a, *43*, 589-593. Arkhangelskaja I V et al 2015 Physics Procedia **74** 212-219

Iskaja I V et al 2016 Journal of Physics: Conference Series, Volume 675, Issue 3, article id. 032015

[4]. Arkhangelskaja I.V. et al., Solar System Research, 2008, 42 (4): 351-358

Gan, W. Q. *Advances in Space Research.* 2005, *35*, 1833-1838.

Kiener, J., Gros, M., Tatischeff, V., Weidenspointner, G. *Astron. Astrophys*. 2006, *445*, 725-733. Topchiev, N. P. et al 2016 Journal of Physics: Conference Series, Volume 675, Issue 3, article id. 032009 Vestrand, W. T., Share, G. H., Murphy, R. J. et al., *Astrophys. J., Suppl. Ser.* 1999, *120*, 409-467,

[1]. R.A. Mewaldt, M. D. Looper, C.M.S. Cohen, G.M. Mason, D. K. Haggerty, M.I. Desai, A.W. Labrador, R.A. Leske, J.E. Mazur. Solar-particle energy spectra during the large events of October- November 2003 and January 2005, Proc. 29th International Cosmic Ray Conference (Pune), 1, 101-104, (2005). American Geophysical Union, Fall Meeting 2005, abstract #SH21A-05, 12/2005.

[2]. Cane, H. V.; Erickson, W. C.; Kaiser, M. L.; Raymond, J. C.; Richardson, I. G.; Duldig, M. L.; Prestage, N. P. Why did the January 20 2005 GLE Have Such a Rapid Onset?

[3]. Kotov, Yu.D. et al.: 2009, Solar-Terrestrial Physics, ed. Kuznetsov V. D., M.: PhysMathlit: 178-258 In the present work we analyze the time profile of 2.223 MeV γ- line from neutron captures by hydrogen nuclei, we also use narrow de-excitation gamma lines from 12C at 4.44 MeV and 16O at 6.13.

[4]. Kuzhevskij, B.M., Miroshnichenko L.I., and Troitskaia, E.V. Gamma-ray radiation with energy of 2.223 MeV and the density distribution in the solar atmosphere during flares. Russian Astronomy Reports, **49**, 566-577, (2005). (In English).

[5]. Kuzhevskij B.M., Kuznetsov S.N., Troitskaia E.V. Development of the solar flare plasma density investigation method based on the 2.2 MeV gamma-line time profile analysis. *Adv. Space Res*. (1998); **22, p.**1141.

[6]. Kuzhevskij, B.M., Miroshnichenko L.I., and Troitskaia, E.V. Gamma-ray radiation with energy of 2.223 MeV and the density distribution in the solar atmosphere during flares. Russian Astronomy Reports, **49**, 566-577, (2005).

[7]. E.V. Troitskaia, W. Q.Gan, B.M. Kuzhevskij, L.I. Miroshnichenko.Solar Plasma Density and Spectrum of Accelerated Particles Derived From the 2.223-Mev Line of a Solar Flare. Solar Physics. **242**. No. 1-2. P. 87 – 99. (2007). http://springerlink.com/openurl.asp?genre=journal&issn=1573-093X, DOI URL: http://dx.doi.org/10.1007/s11207-007-0281-z

[8]. Share G., Murphy R.J., Smith D. et al. in *Talks of the SHINE 2006 Special Session on the 2005 January 20 Event SHINE2006, 2006* (AGU Monograph Series, 2006, **165**), p.177.

[9]. Gingerich, O., Noyes, R.W., Kalkofen, W., et al., Solar Physics, **18,** 347, (1971).

[10].Spruit, H.C. Solar Physics, **34**, 277, (1974).