# The quantitative probabilistic model of the solar energetic particle fluxes description

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## Abstract

The description of a quantitative probabilistic model for peak fluxes and fluences of solar energetic particles from protons up to Ni ions is presented. The model predicts energy spectra of particle fluences or peak fluxes, the values of which should be exceeded with the given probability in a given time period of known or predicted solar activity. The model is based on the methodological principles declared in 1996-1999, but with its basic principles and parameters substantially modified and the basic experimental data complemented.

## 1. Introduction

The first version of the probabilistic solar energetic particle (SEP) model, described earlier (Nymmik 1996, 1998, 1999a), is now revised and corrected according to both a new experimental data set and some discovered inexactitudes, which are essential features of the monitored data (Mottl and Nymmik 2003, 2007). The model is based on a set of principles. First among them is the proportionality between averaged event occurrence rate and solar activity (SA) level, as well as the invariance of the event distribution function with solar activity (SA). Information about these principles, given by Nymmik (1999c), enabled one to predict the probability of occurrence for extremely large events, even during the so-called “quiet” Sun periods. This forecasting was fully realized between 2005 and 2006, when many SEP events occurred, including some extremely large ones.

The fundamentals of the model, describing heavy ion fluxes, have been published in Nymmik (1998, 1999a,b). Although those fundamentals were obtained on the basis of poor and fragmented experimental data, the model has been successfully used by us for applied tasks in areas relating to space research. Since the ACE spacecraft data (ACE) appeared, the part of the model related to heavy particles has been revised and is now ready for further use. In this report, we present the basic features of the model and examples of its use, as well as demonstrating its adequacy and reliability for describing experimental data.

## 2. Basic features and regulations

The model is:

- complete (includes particles from protons to Ni);
- consecutively logical (describes all stages of particle energy spectrum formation);
- probabilistic (all stages of the model’s evolution reflect the probabilistic nature of the SEP phenomenon);
- based on the patterns inherent to the SEP (event occurrence, energy spectrum variance, chemical composition dependence on energy, and the variations thereof).

The model predicts particle energy spectra related to the particle fluences and peak flux occurrences for:

- a given probability to exceed the calculated spectra (referred to, for simplicity, as “probability”) from P=*0.9* to *0.01* (1%);
- any possible SA level;
- any time interval (from *1* month to *3* solar cycles);

- any energy range from *5* to *1000 MeV/nucl* (for special needs, we believe the upper limit to be *10 GeV/nucl*).

The model calculations of the particle energy spectra for a given probability and time period with known or predicted SA are carried out according to the following procedure:

1. For the time period from $T_1$ to $T_2$ with known or predicted solar activity (the smoothed or predicted monthly averaged sunspot numbers $<W_i>$), one needs to calculate the model parameter <n>, which is approximately equal to the expected mean SEP event number, with $E \geq 30$ MeV proton fluence $\geq 10^5$ $cm^{-2}$ (see Nymmik 2006, 2007a,b).

$$< n >= 0.0135 \cdot \sum_{T_1}^{T_2} < W_i > . \qquad (1)$$

The values of the occurrence probability P and <n> are the only inner working parameters of the model (except the particle nature).

In the previous model versions by Nymmik (1998, 1999a,b), we used for the value of <n> a different dependence on Wolf numbers (with power law index 0.7), a different threshold in SEP event size (SEPs with >30 MeV proton fluence $\geq 10^6$ $cm^{-2}$) and yearly averaged sunspot numbers. Therefore, the values of <n> for old and new versions of the model for the same solar activity and mission time period are quite different and not comparable.

2. The energy spectra predicted by the model are given as power functions of the particle momentum (per nucleon) (Nymmik 1999a,b; Mottl et al., 2001; Baranov et al., 2001):

In the present model version, we use 2 modifications of the particle power law momentum spectra: first – for initial spectra, and second – for output spectra.

$$F^{(z)}(E) \cdot dE = F^{(z)}(p)\frac{dp}{dE}dE = C^{(z)}\left(\frac{pc}{p_oc}\right)^{-\gamma^{(z)}}\frac{dp}{dE}dE = C^{(z)}\left(\frac{pc}{p_oc}\right)^{-\gamma^{(z)}}\frac{dE}{\beta} \qquad (2)$$

where $pc = \sqrt{\left(E + 2M_oc^2\right)}$ and $\frac{dp}{dE} = \frac{\sqrt{(pc)^2 + \left(M_oc^2\right)^2}}{pc} = \frac{1}{\beta}$

E is the ion's kinetic energy in MeV/nucl; $M_oc^2 = 938$ MeV is the nucleon rest energy; $\beta = v/c$ is the particle's relative velocity.

- In calculations for initial spectra, we use $p_oc = 239$ MV/nucleon, corresponding to a particle energy E = 30 MeV/nucl and proton rigidity R = 239 MV.

In the case where $E \geq 30$ MeV/nucleon, $\gamma^{(z)}=\gamma_o^{(z)}$,

and if E < 30 MeV/nucl, then $\gamma^{(z)} = \gamma_o^{(z)}\left(\frac{E}{30}\right)^{a^{(z)}}$ (3)

- In the case of output spectra, we use $p_oc = 394$ MV/nucleon, corresponding to a particle energy E = 79.4 MeV/nucl and proton rigidity R = 394 MV.

In cases where E < 79.4, we use also Eq (3); however, in cases of $E \geq 79.4$ MeV/nucleon, we use $\gamma^{(z)} = \gamma_o^{(z)} \cdot b^{(z)}$, (4)

i.e., the output spectra become harder ($b^{(z)} \leq 1$).

Thus, every output spectrum is determined by four parameters: $C^{(z)}$ - spectral coefficient, $\gamma_o^{(z)}$, $a^{(z)}$ - the droop index, and $b^{(z)}$ - the hardening index.

It bears mentioning that all output spectrum parameters of the presented version of the model are quite different from these of the previous version and are therefore not comparable.

According to this explanation, the final model output energy spectra are determined by four parameters of spectra for every particle (fluences and peak fluxes calculated separately) as tables of $C^{(z)}$(<n>,P), $\gamma_o^{(z)}$(<n>, P), $a^{(z)}$(<n>,P), $b^{(z)}$(<n>,P). These tables were calculated for <n> = 1, 2, 4, 8, 16, 32, 64, 128, 256, and 512 and P = 0.9, 0.7, 0.5, 0.3, 0.1, 0.032, and 0.01. The spectral parameters for values different from tabulated <n> are calculated by interpolation of table data.

The model outputs contain Eqs. (1-4), and the final tables of parameters (as well as calculated differential and integral energy spectra) are therefore easy to use. Validity of model results is verified and confirmed by an examination of available experimental data.

## 3. The short description of the used methodology

The model is based on the processing of a very large number ($N > 100000$) of the energy spectra (Eqs. 2-3) for different versions of SEP particle fluences or peak fluxes. Every processed version contains $n_i$ random events according to mean $<n>$ (normal or Poisson distributions are used). For every event, we calculate the parameters of the proton energy spectra in the following sequence:

- The event size $F_{\geq 30\text{MeV}}$ (protons/cm$^2$), determined as the $E \geq 30$ MeV proton fluence, is calculated as a random value of the distribution function and described as a power law with exponential cutoff (Nymmik, 2007c), based on IMP-8 and GOES series spacecraft data.
- The peak flux size is determined as $f_{\geq 30\text{MeV}} = F_{\geq 30\text{MeV}}/5.0\cdot 10^5$ (protons/(cm$^2\cdot$s$\cdot$sr)).

Compared with previous version of the model, the distribution function parameters are slightly adjusted.

- The index of the proton spectrum $\gamma_o^{(i)}$ is calculated as a random value from a lognormal distribution (with mean value $\log<\gamma_o>=0.76$ and standard declination $\log D_\gamma=0.15$), what based only on the GOES spacecraft's uncorrected differential proton flux data.

Compared with the first version (Nymmik 1996, 1998, 1999a), the indices of proton spectra became large (softer spectra) because in the early version, we used the erroneous IMP-8 measured proton spectra data (see Mottl and Nymmik, 2007). This correction was introduced into the intermediate version of the proton fluence model published by Nymmik (2006).

- According to Eq. 2, $C^{(p)} = F_{\geq 30} \cdot (\gamma_0^{(p)}-1)/239.$
- The droop index of the spectra is a random value of the lognormal distribution based on the GOES spacecraft's uncorrected differential proton flux data. The mean value $<a^{(p)}>$ depends on $\gamma_0^{(p)}$ and $F_{\geq 30}$.

The heavy ion energy spectra are based on the ACE SIS measurement data analysis and are calculated using the above proton energy spectra.

- The spectral coefficient for heavy ions is calculated as a lognormal random value of the relative composition with a mean of $E = 30$ MeV/nucl and with a mean square declination that depends on the A/Q ratio (atomic number to ion charge) (Nymmik, 2009).
- The spectral index of heavy ions is calculated from that for protons as a lognormal random value, with the mean value being more than 1.16 times that of protons and with the mean square declination equal to $\log D_\gamma = 0.1$ ($D_\gamma = 1.26$). The value of 1.16 in the present version is less than that of 1.26 used in first version of the model (Nymmik 1998, 1999a).
- Based on the analysis of the experimental data SIS ACE (Nymmik, 2009), the mean value of the droop index in SEP events is smaller than the droop index of the proton spectra and was calculated to be:

$$a^{(z)} = 0.05 + 0.31a^{(p)} \tag{5}$$

This dependence also differs from that given in first version of the model, where, according to data from emulsion technique experiments, the $a^{(z)}$ value depends on the mass-to-charge relation of the particle (Nymmik 1998, 1999a).

The energy spectrum, which is defined by the above parameters, allows one to determine the proton and heavy ion fluences or peak fluxes for any selected energy $E_i$ from 5 to 1000 MeV/nucl. (and in our opinion is correct up to 10 GeV/nucl).

If we are interested in the fluence from any version of N, all fluences of $n_i(E_i)$ must be summarized and, in the case of a peak flux, are needed to choose the maximum flux from $n_i$.

After the calculation of N versions of the energy spectra, we can determine the distribution functions for an arbitrary set of energies $E_i$. Using these functions, it is easy to develop the final energy spectra relative to any needed probabilities.

## 4. Model inputs and outputs.

The model has 3 input parameters:

1. Probabilities P=0.9, 0.7, 0.5, 0.3, 0.1, 0.032, and 0.01.
2. The start and end dates of the mission (T1 and T2, given in months or years).

(For the case where the needed Wolf numbers are different from NASA Boulder's predicted data, the model mission parameter must be recalculated by Eq. 1 with the user's data).

The full internal model calculations are complicated, so the simple output is used in the form of the dependences of the tabulated spectral parameter (C, $\gamma_o$, a, b) on the chosen input parameters <n> and P.

Separate tables exist for particle fluences and peak flux, as well as for ion charges of 1 to 28 for 20 elements – 1, 2, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 22, 24, 26, 28 (p, He, C, N, O, Ne, Na, Mg, Al, Si, P, S, Cl, Ar, K, Ca, Sc, Ti, Cr, Fe, Ni, respectively), excluding Li(3), Be(4), B(5), F(9), Sc(21), V(23), Mn(25), Co(27) and Z > 28. A number of tables are common for a large set of elements. However, it is inconvenient to use the 20 x 8 = 160 tables. Therefore, we use only the tables for p and He. We calculate the remaining heavy particle parameters by correction functions, which depend on <n>, P and Z. In the interactive program, the spectral parameters for intermediate input values <n> that do not appear in the tables (<n> = 1, 2, 4, etc) are calculated by interpolation. The author plans to populate the model for limited interactive use in 2009 on the SINP MSU website.

## 5. Calculation results

### 5.1 Changes in the model spectra compared with the 1996-1999 version

In Fig. 1, we demonstrate the model-calculated integral peak flux energy spectra according to the first (Nymmik 1999a – dashed lines) and the present (solid lines) versions of the model for p, He, O and Fe particles. Data shown are fluxes for an annual mission at solar activity W=100 for the case of fluxes exceeding the calculated values with a probability P=0.16.

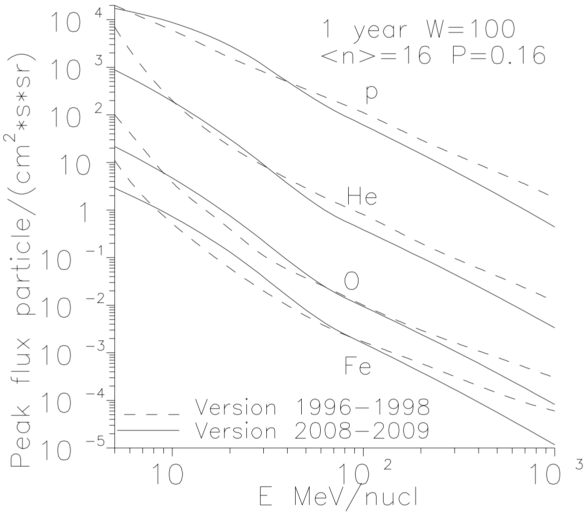

*Fig.1. Model-calculated integral peak flux energy spectra according to original (Nymmik 1999a – dashed lines) and present (solid lines) versions of the model for p, He, O and Fe. Demonstrated data are for a one-year mission at solar activity W=100 in the case of fluxes exceeding the calculated values with probability P=0.16.*

From these data, we can conclude that there are two main differences between the model data. First, the energy spectra at E > 30 MeV/nucleon became softer. This effect is caused by the elimination from the model basis of the proton energy spectra measured by the instrument CPME on IMP-8 due to it being erroneous (Mottl, Nymmik, 2007; Nymmik, 2008). Second, the heavy ion spectra at E < 30 MeV/nucleon became harder. This effect is caused by the difference in the experimental data measured by emulsion and solid track detectors in early experiments (Nymmik, 1999a) and the data of the SIS instrument of the ACE spacecraft (Nymmik, 2009). The first difference in the model spectra is also easily seen from the data shown in Fig. 2, where we demonstrate the integral proton peak fluxes over 22 solar activity cycles (according to the Sladkova et al. 1998 catalogue) and the old and present model calculation results. The present version of the model calculation for the case of probability P = 0.4±0.1 describes well the measurement results from 5 MeV up to 10 GeV. On the other hand, for the spectra based on the old model, the range of probability values extends from 0.5 to 0.01. It is important that we have continuously improved the proton flux model over the recent years. Therefore, in Nymmik (2006) were published the model spectra similar (but not equivalent) to the present model version but different from 1996-1999 versions.

We declare that our model is intended for description of SEP particle peak fluxes and (cumulative) fluences in the range from 5 to 1000 MeV/nucleon. However, from the data in Fig. 2 and from the fact that the energy spectra of the SEP high-energy ion peak fluxes and fluences at E > 30 MeV/nucleon follow a power law (Nymmik 1999a, 2009), it follows that our model may be appropriate up to 10 GeV(/nucleon).

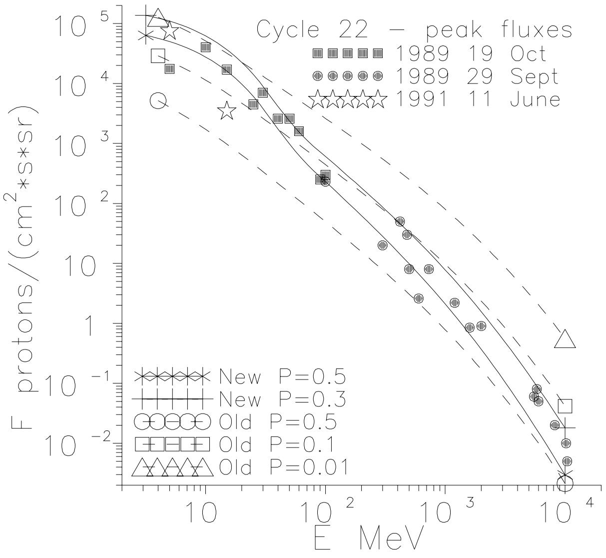

*Fig.2. Model-calculated integral peak flux energy spectra according to original (Nymmik 1996, 1998, 1999a – dashed lines) and present (solid lines) versions of the model for proton peak fluxes. Calculations are for 22 solar activity cycles for probabilities P=0.5, 0.1 and 0.01. Experimental data are for different SEP events from the catalogue of Sladkova et al. (1998).*

In Fig.3, we demonstrate results for the cumulative fluences measured by the spacecrafts GOES for the 22nd solar activity cycle. The results are similar to those for peak fluxes. The present version of the model describes well the experimental data at probability P = 0.5. The old version describes this for probabilities P from 0.1 (at low energies) to 0.7 (at high energies; the spectra for probability 0.7 are not shown in Fig. 3).

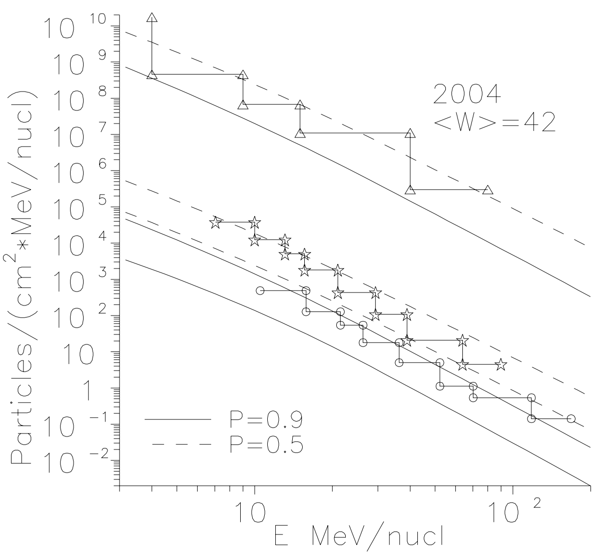

*Fig.3. The model-calculated integral fluence energy spectra according to original (Nymmik 1996, 1998, 1999a – dashed lines) and present (solid lines) versions of the model for protons. Calculations are for 22 solar activity cycles for probabilities P = 0.5 and 0.1. Experimental data are from GOES 6, 7 and 10 measurements.*

Figs 1-3 demonstrate that the present model version performs much better in describing the experimental data than first version of the model does.

## 5.2 Model outputs and independent experimental results

In the cases when the results of the same SEP fluxes measured in different experiments differ from each other, the model does not describe the data of the experiment that was not used as a basis in the model development. This situation was demonstrated by Cleghorn and Badhwar (1999) when they compared our first model version with GOES 6 and 7 measured proton data. They concluded that the model does not always describe these experimental data. However, they were mistaken in attributing this difference to model shortcomings. That model version was developed based on IMP-8 measured proton energy spectra, which differ from those measured by GOES spacecraft.

This fact predicts the pattern that if the correct methodology was used in model development, then the model necessarily reflects all experimental data that serve as its basis. Therefore, it is important to check the model predictions with independent experimental data that were not used as a basis in the model development.

In Fig. 4 we demonstrate the Fe fluence cumulative integral energy spectra, measured in the experiment Platan on the orbital station MIR and recalculated to the interplanetary conditions (Baranov et al. 2002). During the period of Platan measurements (March 1988 – Dec. 1999), several large SEP events had occurred, among them the SEP event Sept. 29, 1989, with hard energy spectra. Therefore, the low energy part of the energy spectra corresponds to a probability of P=0.5, and the high energy part is close to P=0.1. The same holds true for the cumulative fluence of protons measured in that period by the spacecraft GOES-7.

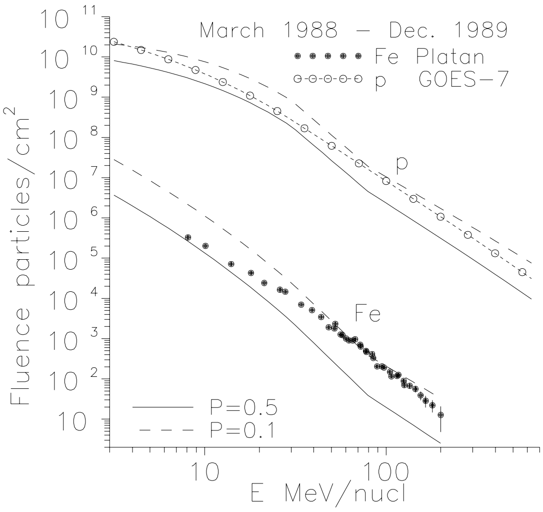

*Fig.4. Measured Fe (Baranov et al. 2002 - black dots) and p (GOES 7 - rings) integral fluences and model-calculated energetic spectra for different probabilities (P = 0.5 and 0.1) exceeding the given data for the period March 1988 – Dec. 1989 according to the present model version.*

## 5.3 Comparison with other model outputs

The main distinction of the present model from other proton fluence models, JPL91 (Feynman et al. 1993) and ESP (Xapsos et al. 1996), is that other models relate only to the hypothetical active Sun years (7-year from solar cycle). Therefore, the fluences predicted by these models for years with W = 50 and W = 150 are the same, while, according to our model, the fluences differ between these years by about a factor of 3. In some papers, for example, in Nymmik (2007a, 2008), we demonstrated the large difference between our model and JPL91 for predicted fluences at E ≈ 60 MeV, caused by the use of the erroneous IMP8 data in the latter model Additionally, there is a noticeable difference between the different model predictions for a small probability region (P ≈ 0.01 or 99% confidence level), caused by different distribution function forms (Nymmik, 2008).

However, the main difference is that our model relates to all of the solar activity levels, including the quiet Sun period. JPL91 and ESP models ignore this period and suppose that the SEP particle fluences in that period are negligible. That is incorrect, as demonstrated during the last quiet Sun period of 2005-2006, during which, a large number of SEP events had occurred, including major events.

In Fig. 5, we show the annual fluences of p, O and Fe in 2006, when solar activity was very low (W = 16). Our model prediction shows that an analogous situation (in terms of measured particle fluences) may occur with probability P = 0.1-0.032 during a one-year period within the 10 to 30 years with a similar solar activity.

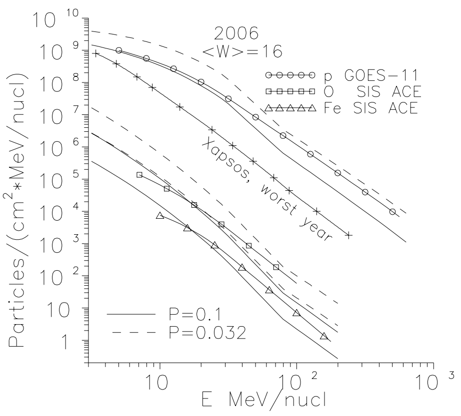

*Fig.5. The differential annual fluence energy spectra for a quiet Sun period (year 2006) – experimental data and calculations by the present model for p, O and Fe for probabilities P = 0.1(solid lines) and 0.032 (dashed lines). Experimental data are: for p – GOES-11; for O and Fe – SIS ACE. Worst-case annual proton spectrum for a quiet Sun period by Xapsos et al. (2004) model (crosses) is also shown.*

In 2004, Xapsos et al. published a special model for the quiet Sun period, which ignored the probabilistic character of SEP events occurrence. The worst annual proton fluence spectrum according to this model is shown in Fig. 5 too. It is seen that the worst-case fluences for the quiet Sun period according to this model are lower by a factor of 20-30 than real fluences in 2006. Moreover, they are 200-300 times lower than fluences predicted for that solar activity by our present model for probability P=0.01.

In 2007, Xapsos et al. published a paper in which were demonstrated the energy spectra of p, He, O and Fe for 2 active Sun years according to the new model PSYCHIC (Fig.6).

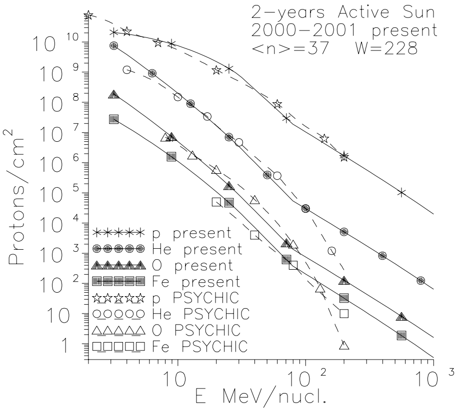

*Fig.6. The model-calculated energy spectra according to PSYCHIC (Xapsos et al, 2007 - dashed lines) for a 2-year active Sun period and according to the present model for equivalent 2-year, W = 114 each (solid lines), periods. Calculated spectra are integral cumulative fluences of p, He, O and Fe. Probability for calculated data to exceed is P = 0.1.*

No details were published regarding this model's development methodology. Nevertheless, we copy these spectra, which correspond to P=0.1, and compare them with those for an analogous period of solar activity by our model. The model-calculated energy spectra for protons and iron by both models coincide. It is surprising that the spectra of He and O calculated by the model PSYCHIC at higher energies differ from protons and iron spectra. In our opinion, this is due to the use of the exponential function instead of a power law in the data analysis. In the case of protons and iron, this replacement is unfeasible because, in this case, the experimental data correspond to higher energies range.

It bears mentioning that for the model PSYCHIC, the same shortcoming is inherent as for models JPL91 and ESP, it being based on the simple hypothesis of identical active years. In addition, as seen from the given spectra, this simplified model is limited by the ranges of SIS instrument energies, and it is possible that the probabilities are limited by the number of SEP events recorded during the active years of the 23 SA cycle.

In 1997 the paper of Tylka et al. were published the results of high energy heavy ion measurements during 1973-1996 on the IMP-8 spacecraft with the CRT instrument. These results were particularly presented as mission-accumulated fluences of He (11-20 and 25-90 MeV/nuc) and Fe (45-79 and 97-432 MeV/nucl) probability for some mission durations.
On the Figs. 7 and 8 we reproduce these results for 1 and 7-year mission durations, as well as our calculations results according to the present model.

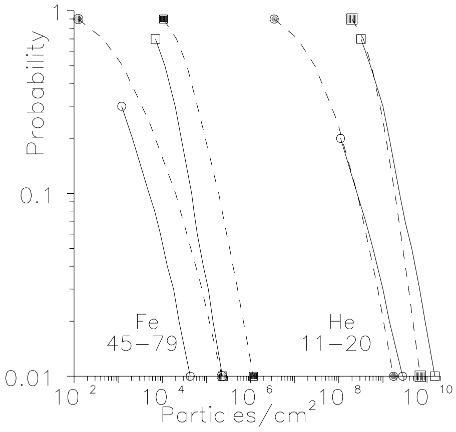

*Fig.7. The predictions for mission-accumulated solar He 11-20 and Fe 45-79 MeV/nucleon fluences according to Tylka et al (1997) (solid lines) and present model (dashed lines) for 1 year (circles) and 7 year (squares) missions at active Sun years.*

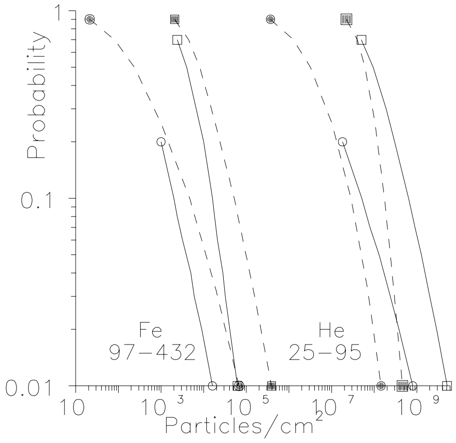

*Fig.8. The predictions for mission-accumulated solar He 25-95 and Fe 97-432 MeV/nucleon fluences according to Tylka et al (1997) (solid lines) and present model (dashed lines) for 1 year (circles) and 7 year (squares) missions at active Sun years.*

From the shown data it follows, that:

- The results of IMP-8 and ACE spacecraft based probabilities coincide for low energy (11-20 MeV/nucl) He fluences for 1 year mission. For longer missions they are close too.
- The high energy (25-90 MeV/nucl) He fluences, measured on IMP-8 (CRT) are larger, than these, calculated from SIS ACE data (from 1.6 to 11 times for probabilities smaller than 0.1 and for different mission durations).
- Fe ion fluences, measured by CRT instrument for the both energy ranges are sufficiently (2-6 times) less than these, calculated from SIS ACE data.

In case of SEP proton fluences we repeatedly have been demonstrated (for example Mottl and Nymmik, 2007, Nymmik, 2008), that the models, developed on the base IMP-8 (CPME instrument) and GOES series spacecrafts data are sufficiently different, because at E>30 MeV the IMP-measured fluxes are exaggerated. As we can see from data, demonstrated on the Figs 7 and 8, we have the same problem with heavy ion fluxes model. It needs to mention, that in Baranov et al. (2002) we demonstrated, that at energies about 60 MeV/nucl the solar Fe fluxes, measured by the instrument CRT, are 4 times less, than the same fluxes, measured by the instrument VLET on the same spacecraft. So, in conditions, when we have not possibility to compare the solar particle fluxes, measured on the IMP-8 and ACE (because of different measurement period), we have an evidence again, that data about solar Fe ions fluxes at E>45 MeV/nucl, measured by CRT instrument, are underestimated (about the same from 2 to 6, or 4, in mean, times).

## 6. Conclusion

A new version of the SEP fluence and peak flux model was developed. The model allows one to calculate the probability of particle (proton and energetic heavy ion) flux to exceed the calculated model value for a given solar activity and over any practically needed time (mission, exposition) period. This model version uses the same methodological base but a corrected and supplemented experimental basis, allowing an adjustment of model outputs compared with the previous version. We demonstrate, that for the heavy ion fluences our model is close to the Xapsos et al., (2007) PSYCHIC model and sufficiently differ from Tylka et al. (1977) model data (what based on the IMP-8 instrument CRT measured heavy particle fluxes).

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