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Upturn in the ratio of nuclei of Z=16-24 to iron observed in the ATIC experiment and the Local Bubble

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Abstract

The ratios of heavy nuclei from Sulfur (Z=16) to Chromium (Z=24) fluxes to the flux of iron nuclei were measured recently in the ATIC-2 experiment. These ratios were the decreasing functions of energy from 5 GeV/n to approximately 50 GeV/n as expected. However, an unexpected sharp upturn in the ratios was observed at energy ~ 50 GeV/n. In this paper, we revise the data and show that the statistical confidence of the observed upturn in the ATIC data is 99.7% and some additional argumets supporting the phenomenon are presented. A possible cause of the upturn is discussed and it is demonstrated that it can be partially understood within a model of 'Closed Galaxy with Bubbles' (CGB). Some features and problems of the CGB model are discussed.

Keywords: cosmic rays, energy spectra, propagation model, leaky-box model, Local Bubble, diffusion coefficient

1. Introduction

It is generally accepted that the ratio of fluxes of secondary cosmic ray nuclei to the fluxes of corresponding parent primary nuclei are decreasing functions of energy. It is a very general consequence of the galaxy diffusion escape length decrease with increasing energies. This expectation was confirmed very well for the energies up to several tens of GeV in HEAO-3-C2 [1], HEAO-3-C3 [2], CRN [3] and some other experiments.

It is supposed for Ar ($Z = 18$) and Ca ($Z = 20$) to be enriched by secondary nuclei [4], therefore decreasing ratio for Ar/Fe and Ca/Fe with energy increasing are expected. These ratios were measured in the energy range from 10 GeV/n to approximately 600 GeV/nucleon (GeV/n in the following) with high statistical accuracy in the HEAO-3-C3 experiment and the results were published in papers [5, 6, 7]. In the energy range from 10 GeV/n to approximately 100 GeV/n the ratios were decreasing function of energy as expected. However there were sharp upturn in the ratios near 100 GeV/n and the ratios were increasing functions of energy above 100 GeV/n. Such behavior was absolutely unexpected but the authors wrote [7] that these growth of ratios might be an instrumental artifact. In the final paper of the HEAO-3-C3 collaboration on this subject [8] the experimental points above 100 GeV/n were not shown at all and the observed upturn was not ever discussed in literature.

Later, an unexpected upturn near the energy of 50–70 GeV/n was observed also in the Ti/Fe ratio measured by the ATIC-2 experiment [9]. The effect was methodically reliable, however the statistics above 100 GeV/n was too low and this upturn was not recognized and discussed as a real phenomenon. The phenomena observed in the HEAO-3-C3 experiment and in the ATIC experiment looked similar but they were methodically unreliable in the first case and statistically insignificant in the second.

In a recent ATIC's paper [10] a new method to measure the ratio under discussion was developed. In this method an averaged spectrum of a number of nuclei in terms of energy per nucleon for a large range of nuclei charges was measured and the ratio of such averaged spectrum to the spectrum of iron was calculated. This method supplies much higher statistics for the ratio than

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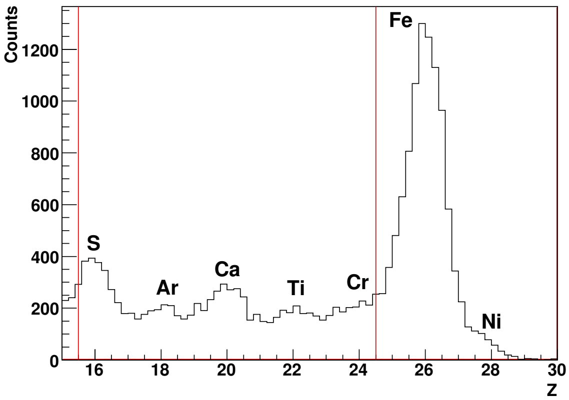

Figure 1: A fragment of charge spectrum as measured by ATIC spectrometer for $E > 60$ GeV per particle. The charge region between two vertical red solid lines corresponds to H^- region (see the text).

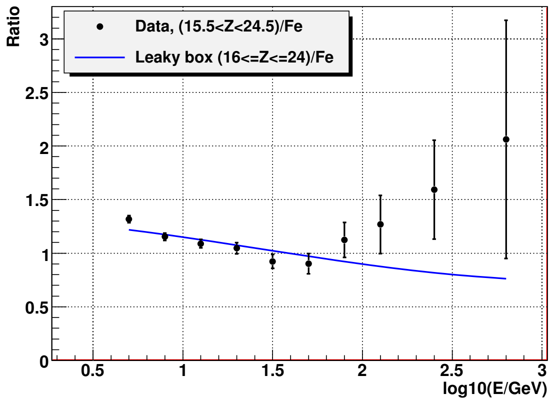

Figure 2: Ratio of heavy nuclei spectrum to iron, H^-/Fe, measured in ATIC experiment [10], together with "naive expectation" based on a simple leaky-box model. E is the energy of nuclei per one nucleon. The position of the upturn point (6-th spectrum point from the left) is approximately 50 GeV/n.

in the case of a single nucleus to iron ratio like Ti/Fe, but the upturn for the ratio, if found, would not be related to one individual nucleus as in all previous papers, but would appear for a large region of charges. The ratio of fluxes for the charge region $H^- = (16 \leq Z \leq 24)$ (see Fig. 1) to the iron flux was measured in [10] and the upturn had been found again. The result is shown in Fig. 2 together with the prediction of a simple leaky box model (naive expectation) with supposition of the same power-law spectra of magnetic rigidity for all nuclei in the source and with propagation model of cosmic rays based on the data of the HEAO-3-C2 experiment [1] (see some details in Section 4). As the fraction of secondary nuclei in the charge region H^- is expected to be high, some decreasing function for the H^-/Fe ratio is expected, but the data are in a sharp contradiction with these expectation. It was argued in [10] that the observed upturn could not be due to a systematic error, but a statistical significance of the phenomenon was not addressed there. In this paper we evaluate the statistical significance of the phenomenon, provide a new confirmation of it from recent experiments and discuss possible explanation of the effect.

2. The statistical significance of the upturn

As can be seen in Fig. 2 an upturn occurs at energy ≈ 50 GeV/n. We will test the hypothesis that the five last points of the ratio in Fig. 2, starting with 50 GeV/n, represent an increasing function of energy. Such a hypothesis means exactly that there is an upturn in the graph in upward direction with a positive derivative.

A simple idea as to fit a straight line to the last five points in Fig. 2 and to investigate the sign of its slope proves to be misleading. The problem lies in the statistical properties of the data points. Each point in the graph is obtained as a ratio of two Poisson's random integer numbers. The denominator may take zero value with a finite and not really insignificant probability. In such a case the ratio has no meaning, and, therefore, the ratio of two Poisson's random numbers, strictly speaking, has a distribution inappropriate for statistical description, being the integral divergent. Consequently, we should reformulate the problem in a meaningful manner.

To do this, we shall consider separately the initial energy spectra that produce the ratio in Fig. 2 in the energy region corresponding the last five points. We approximate each initial differential spectrum by power-law functions like $AE^{-(\gamma+1)}$. Let the power index of the spectrum of the ratio numerator be γ_L (L means 'left', since the spectrum of numerator is related to the charges located in the left part in Fig. 1); and the index of the denominator spectrum be γ_R (R means 'right'). Then the condition $\gamma_R - \gamma_L > 0$ means exactly that the ratio of L to R spectra is an increasing function and this is a hypothesis that could be tested meaningfully.

We apply a maximum likelihood method for Poisson statistics in energy bins of a spectrum to obtain the spectral index. If a differential spectrum is $AE^{-(\gamma+1)}$, then for expected values S_i in the logarithmically-equidistant bins of the spectrum we have

$$S_i = BE_i^{-\gamma}, \tag{1}$$

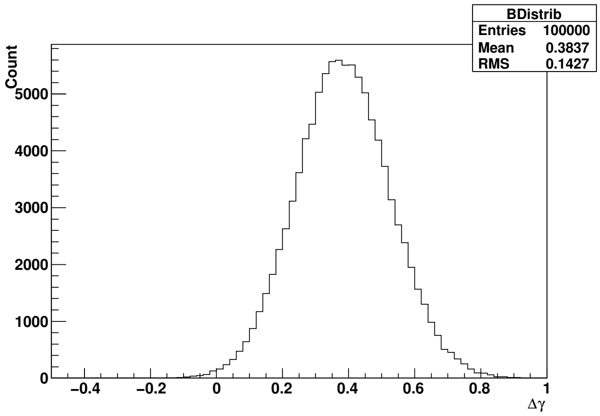

Figure 3: The probability distribution of $\Delta\gamma = \gamma_R - \gamma_L$, corresponding to Fig. 2.

where B is some constant. Taking S_i to be the mean values of Poisson random numbers, it is not difficult to obtain the likelihood function to fit B and γ from the equation (1):

$$F(B,\gamma) = \sum_i [BE_i^{-\gamma} - n_i \ln(BE_i^{-\gamma})], \qquad (2)$$

where n_i is an experimental number of events in the energy bin with number i. Both parameters B and γ are included into function F in an essentially no-linear way and, therefore, we use standard general numerical methods for the minimization of likelihood function.

To estimate the statistical significance of the upturn we proceed in the following way. Each of the initial experimental spectra (L and R) is approximated by the power-law functions (1) using the likelihood method (2). The expectation values S_i are obtained for each energy bin of spectra L and R, and a sequence of pairs of L-like and R-like spectra is generated with Monte Carlo method . Each pair of spectra is processed with the same method as an experimental pair of spectra L and R, and the probability distribution for $\gamma_R - \gamma_L$ difference is build on. The distribution for 10^5 Monte Carlo simulations is shown in Fig. 3.

Within the method used the probability for the difference $\gamma_R - \gamma_L$ to be positive is exactly the statistical significance of the existence of the upturn in upward direction in H^-/Fe ratio, see Fig. 2, above 50 GeV/n. The probability value obtained with the distribution in Fig. 3 is 0.997 and this is high enough to consider the phenomenon seriously.

3. Discussion of the upturn in the ratio H^-/Fe and the ratio of fluxes of abundant heavy nuclei to the fux of iron

As it was seen above, the upturn phenomenon takes place for single nuclei Ar, Ca, Ti separately and for the region of charges $H^- = (16 \leq Z \leq 24)$ as a whole. Therefore the phenomenon looks as a universal one for all charges in H^-. It was confirmed also directly by measuring the ratios $(16 \leq Z \leq 20)$/Fe and $(21 \leq Z \leq 24)$/Fe in the ATIC experiment [10], see Fig. 4, but, of course, with statistics lower than for the whole region H^-. However this universality has to make concern. Actually, we would observe such universality of the phenomenon if the flux of iron nuclei was underestimated in the ATIC experiment by some reasons at high energies. The simplest idea to test this possibility was to measure the ratios of abundant even nuclei to iron. If the spectrum of iron was underestimated at high energies compared to other abundant even nuclei then one should expect the upturn in ratios similar to Fig. 2 and Fig. 4. These ratios were measured in the ATIC experiment and actually show some upturn or a bend [10]. Some important examples are shown in Fig. 5. This phenomenon is also quite universal and takes place starting from carbon for all heavier abundant even nuclei. The ratio O/Fe is shown in the left panel of Fig. 5 and the ratio (C+N+O+Ne+Mg+Si)/Fe is shown in the right panel.

Two points should be noted in relation with this result. First, if the phenomenon is real, it is absolutely unexpected like the upturn in the ratio H^-/Fe. The prediction of a simple leaky-box naive expectation is shown in Fig. 5, left panel, by the solid line. It is seen that the data show a behavior incompatible with this prediction. Second, this result is rather disturbing since really it may suggest an underestimation of the iron spectrum at high energies in the ATIC experiment. A number of methodical tests were considered in the paper [10] and all of them showed no signs of systematic errors. The best way to confirm or disprove the result would be a direct comparison with data of the same type of some other independent experiments. Unfortunately no modern experiments supply ratio of fluxes of cosmic ray nuclei to the flux of iron directly. However high statistical absolute spectra of main heavy nuclei C, O, Ne, Mg, Si, Fe and heavy nuclei in the region of charges H^- – S, Ar, Ca – were measured in two flights of the TRACER instrument: TRACER-LDB1 [11] and TRACER-LDB2 [12]. Therefore using the data of [11, 12] one can calculate the ratios like C/Fe, O/Fe, (S+Ar+Ca)/Fe and compare with similar ATIC data. The results of TRACER ob-

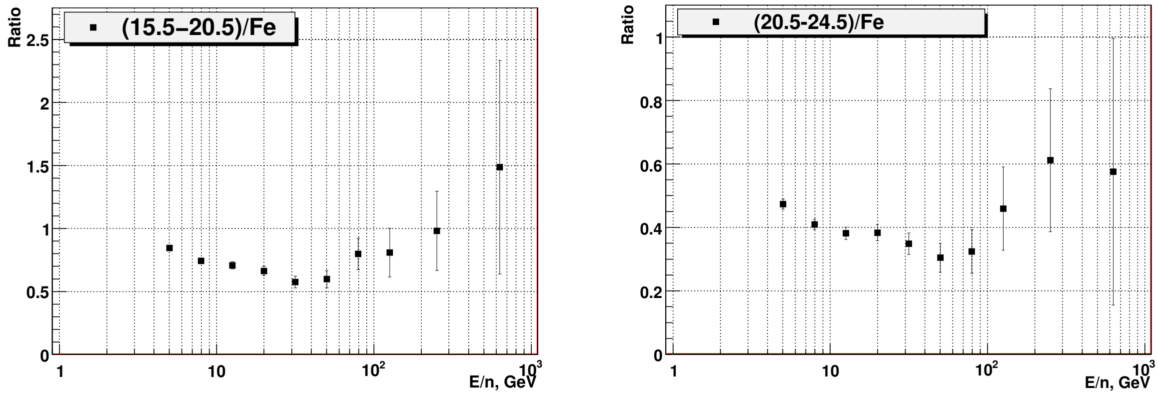

Figure 4: Ratio of fluxes (16 ≤ Z ≤ 20)/Fe and (21 ≤ Z ≤ 24)/Fe measured by the ATIC experiment [10].

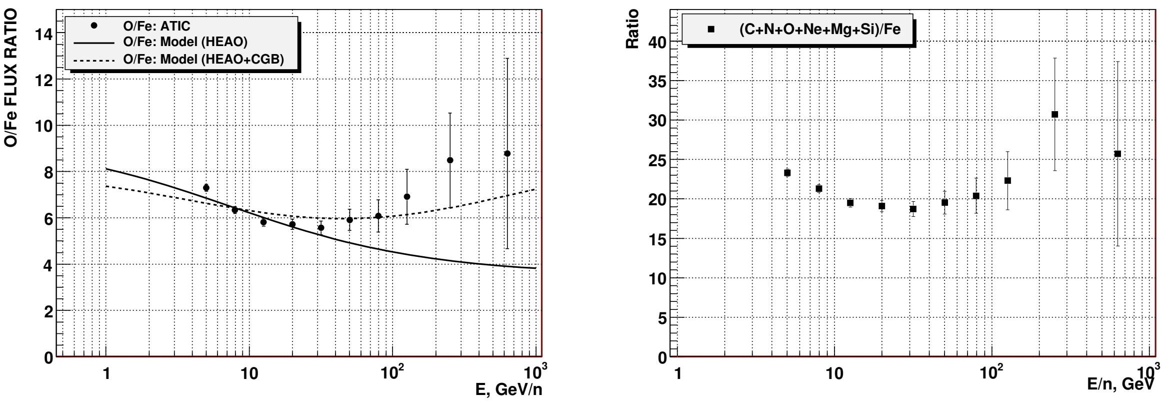

Figure 5: Left panel: Ratio of oxygen flux to the flux of iron measured by the ATIC-2 experiment [10]. Solid line is a "naive expectation" of simple leaky-box model, dashed line – prediction of the model of closed galaxy with bubbles (CGB, see Section 5). Right panel: Ratio of flux C+N+O+Ne+Mg+Si to the flux of iron measured by the ATIC-2 experiment.

tained by this way are not quite direct of course because they are not obtained by the TRACER collaboration itself and a portion of interpolation of the data upon the energy is needed to calculate these ratios. But this is a kind of "almost direct" data. The results of comparison of such almost direct data of TRACER for the ratio (S+Ar+Ca)/Fe with the data of ATIC are shown in Fig. 6. To compare with TRACER we choose the ratio (16 ≤ Z ≤ 20)/Fe measured by ATIC. The last ratio includes also a deposit from the low intensity odd nuclei Cl (Z = 17) and K (Z = 19) and expected to be a bit higher than (S+Ar+Ca)/Fe. The comparison (Fig. 6) confirm this expectation and show good agreement of the TRACER data with the ATIC result. Comparison of the "almost direct" data of TRACER [12] for the ratios C/Fe and O/Fe with the data of ATIC is shown in Fig. 7 and good agreement of the TRACER and ATIC data take place again. Therefore both effects: the upturn in the ratio H^-/Fe and the bend of the ratio of abundant even nuclei to iron are confirmed by almost direct way by the TRACER experiment and we have very strong evidence that both effects are real.

One can assert now that the phenomenon of the upturn observed in the HEAO-3-C3 experiment for Ar/Fe and Ca/Fe with unsufficient methodical reliability and then in the ATIC experiment for Ti/Fe with too low statistical significance now is confirmed with high methodical reliability and sufficiently high statistical significance but not for a ratio of some single nucleus to iron but as an averaged effect for a large region of charges of cosmic ray nuclei H^-/Fe. To study the phenomenon for single nuclei to iron ratio some new experiments are

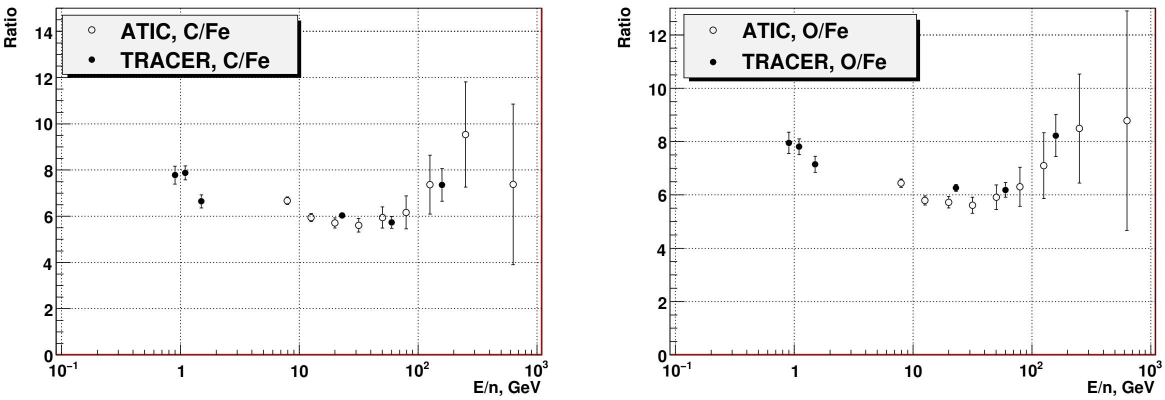

Figure 7: Comparison of the "almost direct" data of TRACER [12] for the ratios C/Fe and O/Fe with the data of ATIC.

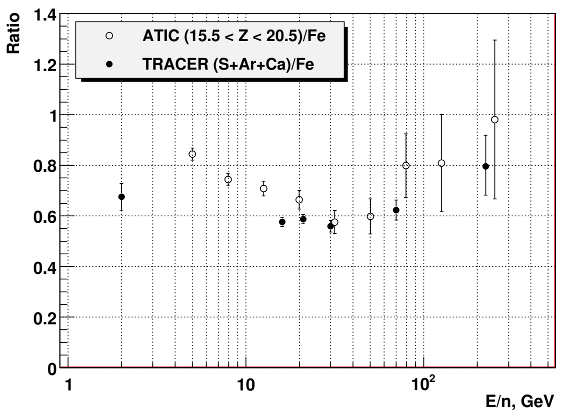

Figure 6: Comparison of the "almost direct" data of TRACER [11] for the ratio (S+Ar+Ca)/Fe with the data of ATIC for the ratio ($16 \leq Z \leq 20$)/Fe.

needed that may provide high statistics for individual nuclei in H^- region and high charge resolution there as well. But now a discussion of possible nature of the observed upturns and bends is meaningful.

4. Towards the interpretation of the upturn in heavy-to-iron nuclei ratios: a simple leaky-box model

We will try to find a cause of the observed upturns among the features of the propagation process of cosmic rays. To describe the transport of particles in Galaxy it is suitable to start with a simple leaky-box approximation. Let $N_1, N_2, \ldots, N_k$ be the secondary nuclei produced by iron spallation. Then the ratio of a combined flux of the secondaries $I_{\Sigma S} = \sum_{i=1}^{k} I_{N_i}$ to the flux of iron nuclei can be written as

$$\frac{I_{\Sigma S}}{I_{\mathrm{Fe}}} = \sum_{i=1}^{k} \frac{\varkappa_{N_i,\mathrm{Fe}}}{\varkappa_{\mathrm{esc}}^{N_i}(\varepsilon) + \varkappa_{N_i}}, \tag{3}$$

where ε is the energy of particle per nucleon, $\varkappa_{\mathrm{esc}}^{N_i} = 1/\lambda_{\mathrm{esc}}^{N_i}$ is the inverse diffusion escape length for the leakage of nuclei N_i with energy ε from the galaxy, $\varkappa_{N_i} = 1/\lambda_{N_i}$ is the inverse nuclear spallation path length in the inter-stellar medium for the nuclei N_i and $\varkappa_{N_i,\mathrm{Fe}} = 1/\lambda_{N_i,\mathrm{Fe}}$ is the inverse partial spallation path-length of iron nucleus to produce a nucleus N_i. Production of secondary nuclei by spallation of other heavier secondary nuclei is neglected in equation (3). The escape length λ_{esc} is considered to be a universal function of rigidity for all nuclei and we choose the standard approximation from [1]: $\lambda_{\mathrm{esc}}(R) = 34.1\, R^{-0.6}\ \mathrm{g/cm^2}$. We use the values of λ_{N_i} as compiled in Ginzburg and Syrovatskii [13], and evaluate the partial path lengths $\lambda_{N_i,\mathrm{Fe}}$ with help of the partial spallation cross sections as given in [14], and under assumption of 90% protons and 10% helium in the interstellar medium.

The ratio H^-/Fe in the ATIC experiment together with prediction of a simple leaky-box model (thin dashed line) for the secondary fluxes calculated with formula (3) are shown in Fig. 8. The leaky-box model (3) accounts for only secondary nuclei in the region H^- and predicts lower ratio H^-/Fe for energies below 50 GeV/n than in the ATIC data. It is a sign of some contribution of primary fluxes to the group H^-. It is quite an expected result, since a prominent contribution of the primary fluxes to group H^- is generally supposed. Obviously, a leaky-box model does not reproduce increasing ratios at energies above 50 GeV/n.

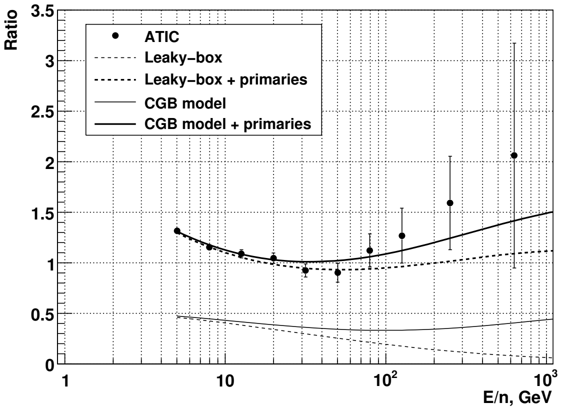

Figure 8: Ratio H^-/Fe measured by ATIC and a number of models (CGB means Closed Galaxy with Bubbles, see the text).

To improve a simple model (3) we should incorporate the primary component to the group H^-. The simplest way is to suppose that all primary nuclei obey the same power-law spectrum. But that is an oversimplification. It was mentioned in Section 3, that the spectra of all abundant primary nuclei C, O, Ne, Mg, Si, being similar to each other, show, however, a certain upturn in their ratio to the iron (see Fig. 5). Let us suppose that not only the abundant primary nuclei C, O, Ne, Mg, Si possess similar source spectra, but the same is valid for all primaries within the group H^-. Then one can fit the H^-/Fe ratio with the sum of the secondary fluxes given by the leaky-box model (3) and a flux of primaries with the shape of spectrum like, for example, oxygen nuclei. The result is shown in Fig. 8 as a thick dashed line. There is a reasonable agreement with to the data at energies $\varepsilon < 50$ GeV/n, but there is no sufficient increase in the ratio at energies $\varepsilon \gtrsim 50$ GeV/n. Thus, a simple leaky-box model with an addition of primary fluxes does not reproduce the data. Some extra ideas are needed to account for a sharp upturn of the H^-/Fe ratio.

5. Model of closed galaxy with super-bubbles

We consider below, as a possibility, a model of a 'closed galaxy' proposed by Peters and Westergaard in [15]. It is supposed in this model, that there are a number of compact regions in the galaxy that contain CR sources and they can be described by a simple leaky-box model in relation to the diffusion leakage of particles from each such region. Moreover, it is assumed that all the CR sources are concentrated in such local areas. In the original paper [15] it was supposed that these compact regions were the galaxy arms, but they can be as well super-bubbles produced by supernova explosions. The last opportunity looks reasonable if the supernovas explode preferably within star associations where a star formation process occurred shortly before and massive, short-living stars were created. The idea that super-bubbles can play an important role in forming the cosmic rays spectra was widely discussed (see [16, 17] and references herein). The exact nature of these local regions does not matter very much for the model, but for definiteness we will consider the super-bubbles and call the model a 'Closed Galaxy with Bubbles' (CGB). The second assumption of the model is that the entire galaxy is closed for the diffusion leakage. And it is accepted that the Sun (and observers as well) is located within one of the bubbles, a Local Bubble, and the purpose of the model is to predict the CR fluxes for various nuclei within the Local Bubble.

A total CR flux in a bubble is, then, comprised of two parts [15]: 1) a local flux which can be described by the usual leaky-box model when applied to the bubble and 2) a global equilibrium galaxy flux (hereinafter we call it a 'bulk flux'), which can also be described by a model similar to the leaky-box model applied to the entire galaxy, but with an additional condition of $\lambda_{\mathrm{esc}}(\varepsilon) \simeq \infty$. The last condition means actually that the diffusion length is much longer than all nuclear spallation lengths under interest and for the considered energies. This condition, of course, can not be valid for all energies. There is one free parameter in our model that represents the fraction of the bulk flux in the total flux within a bubble, that is unknown apriori and is to be fitted to the data.

The only sources of CR for the bulk flux within a frameworks of CGB model are the surfaces of the bubbles. With a standard assumption that the probability for a particle to leave a volume does not depend on the already travelled path within the volume one can obtain the equation for a modified bulk source:

$$Q_{\mathrm{bulk}}(\varepsilon) = \frac{\varkappa_{\mathrm{esc}}(\varepsilon)}{\varkappa_{\mathrm{esc}}(\varepsilon) + \varkappa}\, Q(\varepsilon). \qquad (4)$$

Here $Q(\varepsilon)$ is the spectrum of some nucleus in the source within a bubble, $\varkappa_{\mathrm{esc}}(\varepsilon)$ is the inverse escape length for the nucleus from a bubble, and $\varkappa$ is the inverse nuclear interaction length for this nucleus. Using equation (4) and a standard formula of leaky-box approximation when applied to the bubble and to the galaxy, one can obtain the ratio of total flux of a secondary nuclei N_i to

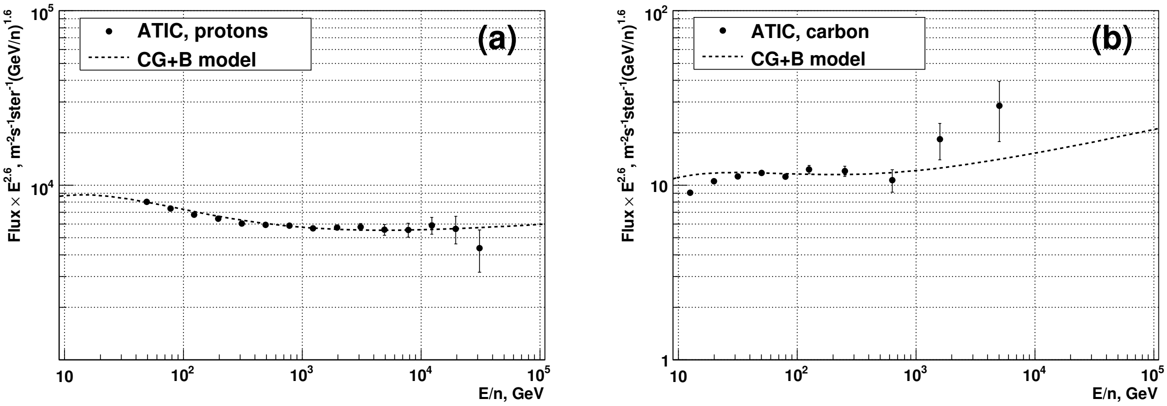

Figure 9: Fit of abundant nuclei spectra measured by ATIC-2 with the CGB model: (a): protons, $\alpha_{\text{source}} = 2.55$; (b); carbon, $\alpha_{\text{source}} = 2.45$.

the flux of iron in CGB model, as:

$$\frac{I_{N_i}(\varepsilon)}{I_{\text{Fe}}(\varepsilon)} = \frac{\dfrac{\varkappa_{N_i,\text{Fe}}}{\varkappa_{\text{esc}}^{N_i}(\varepsilon) + \varkappa_{N_i}} + K\,\dfrac{\varkappa_{N_i,\text{Fe}}}{\varkappa_{N_i}}\,\dfrac{\varkappa_{\text{esc}}^{\text{Fe}}(\varepsilon)}{\varkappa_{\text{Fe}}}}{1 + K\,\dfrac{\varkappa_{\text{esc}}^{\text{Fe}}(\varepsilon)}{\varkappa_{\text{Fe}}}}, \quad (5)$$

where K describes the contribution of the bulk flux to the total one. For the flux of some group of nuclei we shall do a summation over index i in equation (5).

The value of the factor K determines the position of minimum of the ratio of secondaries to a primary, therefore K could be easily obtained by fitting to the data. The predictions of CGB model for the fluxes of secondaries only in the group H^- with $K = 0.2$ are shown in Fig. 8 by thin solid line. The complicated behavior of the model with its decreasing and increasing regions of ratios is a result of competition between the local and the bulk fluxes. The thick solid line shows the CGB model prediction together with the contribution of primary fluxes, exactly in the same way as it was described above for the simple leaky-box model. It is seen that CGB model together with the contribution of primary fluxes agrees reasonably well with the data.

CGB model predicts also ratio of abundant even nuclei fluxes to the flux of iron, and this prediction is different from the prediction of the standard leaky-box model. The mathematics is similar to that, used to obtain the formula (5). The prediction of the CGB model for O/Fe ratio is shown in Fig. 5, left panel, by dashed line for the same parameter $K = 0.2$ as in Fig. 8. It is seen in Fig. 5 that the CGB model predicts a bend of ratio to the upward direction and this prediction is closer to the data than the prediction of the simple leaky-box model. It is an advantage of the CGB model, but the bend looks too weak and it may be a trouble of the model. There are also a number of other problems with the CGB model.

The appropriate fits to the proton and carbon ATIC's spectra with the CGB model are shown in Fig. 9(a) and Fig. 9(b), respectively. We have to choose the source spectral indexes $\alpha(\text{protons}) = 2.55$ and $\alpha(\text{carbon}) = 2.45$ to fit the data. These are very soft primary spectra and it can mean a problem for the CGB model. This result is quite generic for the close galaxy models since at energies above 100–200 GeV/n the bulk flux dominates and there is no diffusion leakage of cosmic ray from the galaxy for the bulk flux. Therefore the observer measures almost undisturbed source spectrum at high energies and the source spectral index is approximately equal to measured spectral index which is near 2.5–2.6.

There is other important physical consequence of the CGB model. If one consider the leakage from the Local Bubble in the diffusion approximation, the diffusion coefficient can be estimated as [18, p. 124]: $D(\varepsilon) \sim \rho c H^2/\lambda_{\text{esc}}(\varepsilon)$, where H is some characteristic size of the system. In the case of leakage from the Galaxy, H means the half-width of the Galaxy magnetic halo $\sim$ 4 kpc, but in the context of CGB model, H means the half-size of the Local Bubble ($\sim$ 100 pc [19, 20]). Since λ_{esc} (in g/cm^2) is the same in both cases, and the half-size of the Local Bubble is much less than the half-width of the halo, and the gas density within the bubble is expected to be much less than the mean density in the Galaxy [19, 20], then, the CGB model predicts the diffusion coefficient value much smaller ($\sim$3 orders of magnitude or even more) than normally accepted one. Such conclusion may be considered as a problem of the

CGB model. This estimate supposes a free escape of particles from the border of a bubble, however this inference can be invalid. An alternative explanation of the strong confinement of cosmic rays in the Local Bubble might be reflection of charged particles by the termination shock of the bubble [17].

Finally, the situation with B/C ratio in the relation to CGB model is not quite clear now. There is a lack of published data at sufficiently high energies (above 50 GeV/n) but there are strong reasons to suppose that there is no sharp upturn in the B/C ratio near the energy 50 GeV/n similar to H^{-}/Fe ratio. If so, the CGB model in its present form does not describe B/C data. Also, in this case, independently on any models, we have very intriguing situation. The physics describing B/C and H^{-}/Fe ratios look quite similar but actual behavior of the data is absolutely different. Why? It is a great challenge for the future experiments and theory.

Thus, we do not think that the CGB model is the final solution of the problem of the nature of observed in the ATIC experiment upturns. However the model may grasp some essential features of a correct explanation, therefore the model may yet represent a methodical interest.

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References

[1] J. Engelmann, P. Ferrando, A. Soutoul, P. Goret, E. Juliusson, L. Koch-Miramond, N. Lund, P. Masse, B. Peters, N. Petrou, I. Rasmussen, Charge composition and energy spectra of cosmic-ray nuclei for elements from Be to Ni – Results from HEAO-3-C2, A&A 233 (1990) 96–111.

[2] W. Binns, T. Garrard, M. Israel, M. D. Jones, M. Kamionkowski, J. Klarmann, E. Stone, C. Waddington, Cosmic-ray energy spectra between 10 and several hundred gev per atomic mass unit for elements from ar-18 to ni-28 - results from heao 3, ApJ 324 (1988) 1106–1117.

[3] S. Swordy, D. Mueller, P. Meyer, J. L'Heureux, J. Grunsfeld, Relative abundances of secondary and primary cosmic rays at high energies, ApJ 349 (1990) 625–633.

[4] M. Shapiro, R. Silberberg, C. Tsao, Composition of relativistic cosmic rays near the Earth and at the sources, in: Space Research XII, Akademic-Verlag, Berlin, 1972, pp. 1609–1615.

[5] M. Jones, J. Klarmann, E. Stone, C. Waddington, W. Binns, T. Garrard, M. Israel, Energy spectra of elements with $18 \leq z \leq 28$ between 10 and 300 GeV/amu, in: Proc. of the 19th ICRS, Vol. 2, 1985, pp. 28–31.

[6] M. Israel, M. Jones, M. Kamionkowski, J. Klarmann, E. Stone, C. Waddington, W. Binns, T. Garrard, Cosmic-ray energy spectra between ten and several hundred gev/amu for elements from (18)ar to (28)ni – results from HEAO-3, in: Proc. of the 20th ICRS, Vol. 1, 1987, pp. 330–333.

[7] W. Binns, T. Garrard, M. Israel, M. D. Jones, M. Kamionkowski, J. Klarmann, E. Stone, C. Waddington, Cosmic-ray energy spectra between 10 and several hundred gev per atomic mass unit for elements from ar-18 to ni-28 - results from *heao* 3, ApJ 324 (1988) 1106–1117.

[8] V. Vylet, C. Waddington, W. Binns, T. Garrard, M. Israel, J.Klarmann, M. Metzger, Energy spectra between 10 and several hundred GeV/nucleon for elements from $_{18}$Ar to $_{23}$V: Results from HEAO-3, in: Proc. of the 21th ICRS, Vol. 3, 1989, pp. 19–22.

[9] V. Zatsepin, A. Panov, N. Sokolskaya, J. J.H. Adams, H. Ahn, G. Bashindzhagyan, J. Chang, M. Christl, A. Fazely, T. Guzik, J. Isbert, K. C. Kim, E. N. Kouznetsov, M. Panasyuk, E. S. Seo, J. Watts, J. P. Wefel, J. Wu, Energy dependence of Ti/Fe ratio in the galactic cosmic rays measured by the ATIC-2 experiment, Astronomy Letters 35 (2009) 338–342.

[10] A. D. Panov, N. V. Sokolskaya, V. I. Zatsepin, J. H. Adams, H. S. A. Jr., G. L. Bashindzhagyan, J. Chang, M. Christl, A. R. Fazely, T. G. Guzik, J. Isbert, K. C. Kim, E. N. Kouznetsov, M. I. Panasyuk, E. S. Seo, J. W. Watts, J. P. Wefel, J. Wu., Upturn observed in heavy nuclei to iron ratios by the ATIC-2 experiment, J. Phys.: Conf. Ser. 409 (2013) 012036.

[11] M. Ave, P. Boyle, F. Gahbauer, C. Höppner, J. Hörandel, M. Ichimura, D. Müller, A. Romero-Wolf, Composition of primary cosmic-ray nuclei at high energies, ApJ 678 (2008) 262–273.

[12] A. Obermeier, M. Ave, P. Boyle, C. Höppner, J. Hörandel, D. Müller, Energy spectra of primary and secondary cosmic-ray nuclei measured with TRACER, ApJ 742 (2011) 14.

[13] V. Ginzburg, S. Syrovatskii, The Orign of Cosmic Rays, Pergamon Press, 1964.

[14] P. Ferrando, P. G. W.R. Webber and, J. Kish, D. Schrier, A. Soutoul, O. Testard, Measurement of ^{12}c, ^{16}o, and ^{56}fe charge changing cross sections in helium at high energy, comparison with cross sections in hydrogen, and application to cosmic-ray propagation, Phys. Rev. C 37 (1988) 1490–1501.

[15] B. Peters, N. Westergaard, Cosmic ray propagation in a closed galaxy, Astrophysics and Space Science 48 (1977) 21–46.

[16] R. Streitmatter, F. Jones, Superbubbles and local cosmic rays, in: Proc. of the 29th ICRS, Vol. 3, 2005, pp. 157–160.

[17] A. Erlykin, A. Wolfendale, A new component of cosmic rays?, Astropart. Phys. 35 (2012) 449–456.

[18] T. Gaisser, Cosmic rays and particle physics, Cambridge University Press, N.Y., 1990.

[19] P. Frisch, D. York, Synthesis maps of ultraviolet observations of neutral interstellar gas, ApJ Lett. 271 (1983) L59–L63.

[20] T. Berghoefer, D. Breitschwerdt, The origin of the young stellar population in the solar neighborhood – a link to the formation of the Local Bubble?, A&A 390 (2002) 299–306.