Pulsar origin of the fine structure of the cosmic ray electron spectrum measured by the ATIC experiment and prediction of a fine structure in the positron abundance

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Abstract: A high amplitude fine structure was found between 200 and 600 GeV in the cosmic ray electron spectrum measured by ATIC-2 and ATIC-4 experiments [1], and the statistical confidence of the phenomenon was estimated there as 99.7%. In this paper we show that the annihilation or decay of dark matter particles could not be the cause of the observed fine structure. However, the sharp peaks of the structure could be fitted by spectra of a number of nearby pulsars, if the primary spectra of pulsars have sufficiently high energy cut together with spectral indexes expected for typical pulsar wind nebulae. The pulsar origin of the fine structure predicts an existence of a fine structure in the positron fraction spectrum in the energy range of 200-600 GeV. This prediction can be tested in subsequent high-resolution experiments.

Keywords: cosmic ray electrons, positrons, energy spectrum, positron fraction, dark matter, pulsars

1 Introduction. Fine structure in the electron spectrum measured by the ATIC experiment

The ATIC (Advanced Thin Ionization Calorimeter) balloon-borne spectrometer was designed to measure the energy spectra of nuclei from hydrogen to iron with an individual resolution of charges in primary cosmic rays for energy region from 50 GeV to 100 TeV. It was shown that ATIC was capable of not only measuring the spectra of cosmic ray nuclear components but, also, the spectrum of cosmic ray electrons [2] (in this paper electrons will be taken to mean negative electrons and positrons). In order to separate electrons from a much higher background of protons, the differences in the shower development in the apparatus for electrons and nuclei are used. The spectrum of cosmic ray electrons, measured by ATIC in this way, was published in the paper [3]. A bump-like feature between 300 GeV and 800 GeV was found in the measured spectrum. This stucture was widely discussed later in the relation to the possible dark matter particles annihilation or decay.

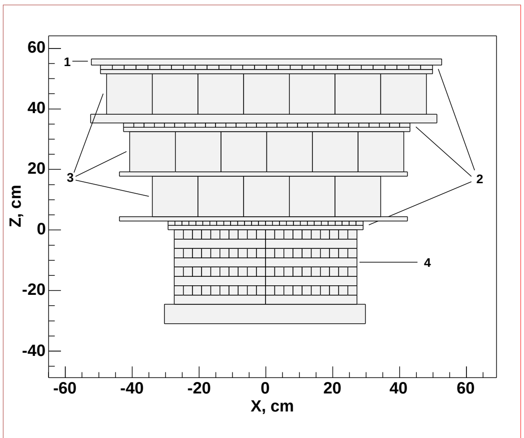

Figure 1: The ATIC spectrometer (ATIC-2 configuration). 1–silicon matrix, 2–scintillator hodoscopes, 3–carbon target, 4–BGO calorimeter.

The ATIC apparatus is comprised of a fully active bismuth germanate (BGO) calorimeter; a carbon target with embedded scintillator hodoscopes; and a silicon matrix that is used as a main charge detector as it shown in Fig. 1. The ATIC spectrometer had three successful flights around the South Pole in 2000–2001 (ATIC-1, test flight), 2002-2003 (ATIC-2) and 2007-2008 (ATIC-4). The calorimeter of ATIC was thick for electrons. It was $18X_0$ (X_0 is a radiation unit) in ATIC-2 and $22X_0$ in ATIC-4. As a result, the energy resolution for electrons of the instrument was high in the total energy range of 30 GeV–1 TeV. The simulation predicted and the beam tests confirmed that the resolution, in terms of half width on the half height, was not worse than 3% [4]. Such high resolution, together with relatively high statistics, allows a meaningful measurement of the electron spectrum in the high-resolution mode – with energy bins as small as 5–8% (0.020–0.035 of decimal logarithm of energy).

High-resolution measurements of the electron spectrum were carried out for ATIC-2 and ATIC-4 flights in [1] and revealed a fine structure in the region of "ATIC bump"(200–600 GeV) which was reproduced in both flights, see Fig. 2. The spectra in Fig. 2 are shown without subtraction of a proton background, which should be smooth, and without correction for the residual atmosphere, but it does not influence the short-scale fine structure.

The statistical significance of the fine structure was estimated in [1] by two different ways. The first way was to use the usual χ^2-test for the total ATIC-2+ATIC-4 spectrum. The second one was to use the degree of correlation between the structures measured separately by ATIC-2 and ATIC-4. In each case the statistical significance of the fine structure was estimated as 99.7%. The observed fine structure is expected to be stable against all known possible systematic errors since they cannot produce any

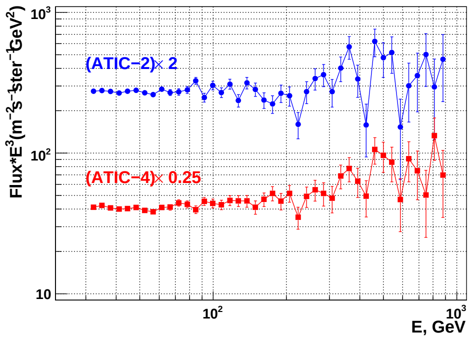

Figure 2: The fine structure of the electron spectrum as measured in the ATIC-2 and ATIC-4 experiments [1]. The size of energy bin is 0.035 of the decimal logarithm of energy (8.4%).

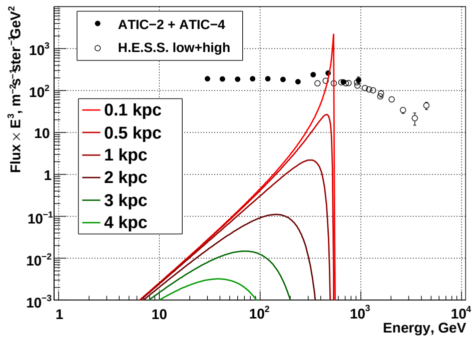

Figure 3: A family of electron spectra produced by a single DM clump for different distances from an observer to the clump. The total mass of the clump is about $2.5 \cdot 10^6 M_\odot$, the total annihilation rate is $Q_0 = 1.7 \cdot 10^{34} s^{-1}$ with delta-like spectrum of electrons concentrated at 550 GeV. No enhancing of annihilation like Sommerfeld effect. From [8].

short-scale structures in the spectrum. The observed fine structure passed and survived a number of tests on stability against possible systematics [1]. The observed phenomenon poses the question: what is a possible explanation of it?

2 Dark matter and the fine structure of the electron spectrum

The amplitude of the fine structure measured by ATIC is very large, therefore the mechanism responsible for the fine structure creation should be responsible also for a large fraction of the electron flux for energies above 200 GeV, where the fine structure is observed. Therefore the question about dark matter may be formulated as follows: could annihilation or decay of dark matter particles produce large electron flux above 200 GeV concentrated in several narrow peaks as in Fig. 2?

High energy electrons and positrons may be a product of annihilation or decay of dark matter particles. Dark matter may exist in our Galaxy in two forms: as a large halo, that may be considered as uniform in the neighborhood of the Sun, and as subhalos or clumps with various masses and sizes. The uniform component of the dark matter distribution could in principle produce only one peak in the electron spectrum or even some smooth bump-like structure withot sharp peaks at all. It is known from many papers, see for example [5, 6, 7, 8]. The origin of such behavior is a permanent character of such a source of electrons. Various ages of electrons is mixed in observations, different ages of electrons are characterized by different decreasing of their energies due to radiative losses, therefore initial sharp annihilation or decay energy peak of electrons (if exists) is spread to a wide energy range.

A dark matter clump may in principle produce a very sharp peak, if the clump is located very close to the Sun [8]. The farther the clump, the lower the energy of the peak due to radiative cooling of electrons, and smoother the peak due to mixing of different ages of electrons [8, 9] (see Fig. 3). Even if there are a number of dark matter clumps at different distances from the Sun that may deposit to the observed electron spectrum, they actually could produce some wave-like structure in the electron spectrum, but only one peak may be more or less sharp (for example, see [10]). Therefore dark matter annihilation or decay could not be responsible for large amplitude fine structure observed by the ATIC experiment.

3 Fitting of the fine structure by nearby pulsars

In fact a fine structure, which is very similar to one observed in the ATIC experiment, was independently predicted in paper [11] (Fig. 4). The result was obtained as a sum of standard diffusion background of electrons and positrons according [12] and a sum of single-pulsar electron spectra generated by pulsars from ATNF catalog. The obtained spectrum should not be considered as an exact quantitative prediction because the model was very simplified: the parameters (spin-down energy, spectral source index, cut energy) were assumed the same for all pulsars etc. However qualitatively the predicted picture Fig. 4 is similar to the experimental data in Fig. 2. Particularly, both the observed and the predicted structures are located above 200 GeV. The only essential difference is higher observed amplitude of the fine structure than the predicted one. Therefore the question arises: how the fine structure of such high amplitude may be obtained by a reasonable way?

Obviously, a key to solution of this problem is how a single pulsar electron spectrum may have a shape of sharp peak with sufficiently high amplitude and at different energy positions. One way to solve this problem was proposed in [11]. It was noted in [11] that the older is the pulsar, the sharper is the peak in its electron spectrum. This is a result of more fast cooling of high-energy electrons than electrons with lower energies. This effect is demonstrated in the the upper panel of Fig. 5 where one can see also that the position of a single-pulsar electron peak is determined by the age of the pulsar. There are also other ways to obtain sharp single-pulsar electron peaks. A number of examples are shown in Fig. 5. All these pictures were generated as solutions of the diffusion equation for the transport of cosmic ray electrons with burst-like approximation for emission of electrons by a pulsar. The details of calculations are described in [8]. For all spectra the same set of param-

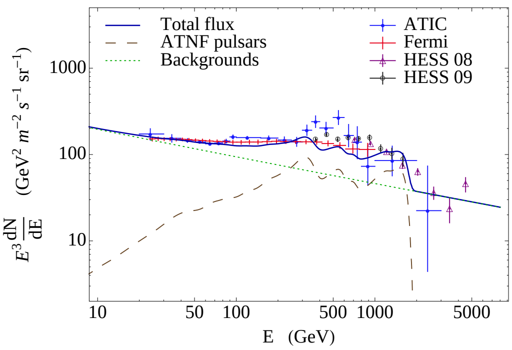

Figure 4: The predicted electron spectrum for pulsars in the ATNF catalog together with conventional background as calculated in [11, FIG.4] (reproduced by permission of the authors).

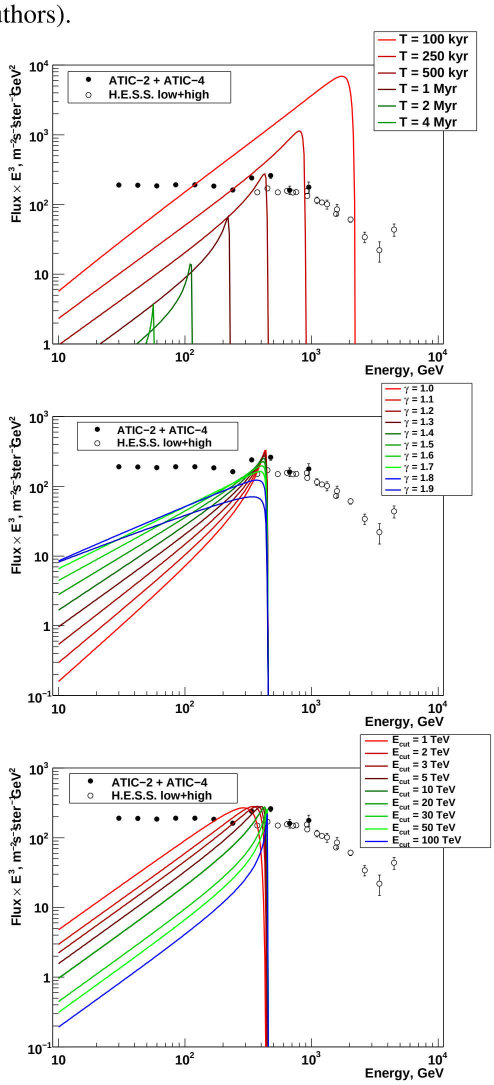

Figure 5: Three series of a single-pulsar electron spectra for the set of basic parameters of pulsar and interstellar media as: $r = 250\,\mathrm{pc}$, $T = 500\,\mathrm{ky}$ $\gamma = 1.3$, $\eta W_0 = 5 \cdot 10^{49}$ erg, $E_{cut} = 20\,\mathrm{TeV}$, $b_0 = 1.4 \cdot 10^{-16}\,(\mathrm{GeV} \cdot \mathrm{s})^{-1}$, $D_0 = 3 \cdot 10^{28}\,\mathrm{cm}^2 \cdot \mathrm{s}^{-1}$, $\delta = 0.3$ and varying parametrs on the backgrond of the basic parameters as shown in panels with graphs. For comparison the data of ATIC experiment and H.E.S.S. [13] are shown.

eters of pulsar and interstellar medium was used, as presented in the caption of Fig. 5, except one varying parameter for each panel, as shown in the figure. The parameters of a pulsar are: r – distance to pulsar; T – age of pulsar; γ – spectral index of the source spectrum; ηW_0 – the spin-down energy transferred to the electron-positron pairs; E_{cut} – upper cut-off energy for the source spectrum (exponential cut-off). The parameters of interstellar medium are the following: b_0 is a factor that controls radiative losses of electrons by equation $dE/dt = -b_0 E^2$; D_0 and δ are factors that control the dependency of the diffusion coefficient on energy by the formula $D(E) = D_0(E/\mathrm{GeV})^{\delta}$.

Our task is not to identify each observed feature in the fine structure of the electron spectrum measured by ATIC with some definite known pulsar. Our opinion is that this problem is too difficult to be solved now since the distances to the nearby pulsars and some other parameters were known poorly. Also, since the birth velocities of pulsars, due to asymmetric supernova explosions, were very high, the pulsars known locations have little in common with those locations where the pulsars had ejected the electrons. The mean birth velocity was 450 ± 90 km/sec and a velocity above 1000 km/sec was not rare [14]. Typically, the difference between a current pulsar location and a location of burst-like ejection of the electrons by this pulsar may be hundreds of parsecs, and it is exactly the scale of distances from nearby pulsars to the Sun. Therefore, the distances to actual burst-like sources are almost completely unknown and it is meaningless to try to fit the current positions of the pulsars. Consequently, we tried to demonstrate only that the fit of the fine structure by pulsars was possible with some reasonable suppositions.

By combining various ways to generate single-pulsar peaks, the measured fine structure can be fitted by many different ways. Fig. 6 shows an example of a fit of the electron spectrum generated by several pulsars with the conventional-like background. The propagation parameters for Fig. 6 were the same as in Fig. 5. The background was obtained by solution of diffusion equation in thin Galaxy disk and thick magnetic halo approximation [8]:

$$Q_{e^-+e^+}(E) = Q_0 E^{-(\gamma_0+\Delta)} + Q_{s,e^-} E^{-(\gamma_s+\Delta)} + Q_{s,e^+} E^{-(\gamma_s+\Delta)},$$

where $Q_0 = 280, Q_{s,e^-} = 15.7, Q_{s,e^+} = 41.5$ are amplitudes of the primary negative electron flux, secondary negative electron flux, and secondary positron flux respectively (all in $\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{ster}^{-1}$); $\Delta = \delta + 1/2$; $\gamma_0 = 2.15$ is the spectral index of negative electrons in the source; $\gamma_s = 2.6$ is the source index for secondary electrons and positrons (it is approximately the averaged spectral index of cosmic ray nuclei). The parameters of four pulsars that produce four main peaks in Fig. 6 were (from right to left): $r = 100\,\mathrm{pc}, T = 800\,\mathrm{kyr}, \eta W = 3.0e49\,\mathrm{erg}$; $r = 500\,\mathrm{pc}, T = 600\,\mathrm{kyr}, \eta W = 4.0e49\,\mathrm{erg}$; $r = 500\,\mathrm{pc}, T = 420\,\mathrm{kyr}, \eta W = 3.0e49\,\mathrm{erg}$; $r = 280\,\mathrm{pc}, T = 270\,\mathrm{kyr}, \eta W = 0.5e49\,\mathrm{erg}$. For all pulsars $E_{cut} = 20$ TeV, $\gamma = 1.1$. Below 200 GeV, the data were fitted by eight distinct pulsars; however, it should be considered only as an illustration. Also, this region could be fitted by a continuum of far pulsars, as was done in paper [11]. The generated electron peaks are very sharp within the used simple analytical model. In reality the single-pulsar peaks are smeared out of course by the ISM inhomogeneity. However, this smearing is expected to be about only 5% for $E \sim 1$ TeV electrons [11]. Such a small smearing could not change notably the obtained picture.

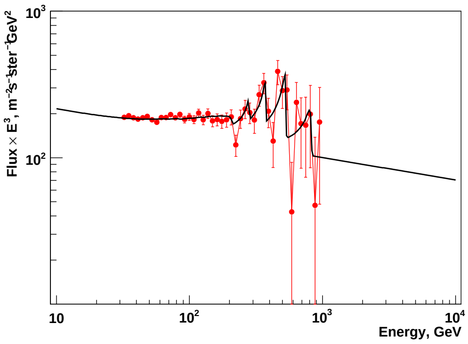

Figure 6: An example of a fit of the measured fine structure in the electron spectrum by several nearby pulsars with conventional background.

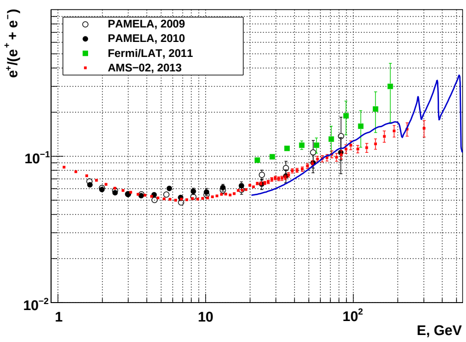

Figure 7: The positron fraction calculated for the model of Fig. 6. The experimental data are: PAMELA, 2009 [17]; PAMELA, 2010 [17]; Fermi/LAT, 2011 [18]; AMS-02, 2013 [19].

The points in Fig. 6 denote the high-resolution electron spectrum measured by ATIC-2+ATIC-4 with the correct absolute normalization. The proton background is subtracted; the scattering of electrons in the residual atmosphere above the apparatus is corrected (see [1] for details). The energy bin size is 0.035 of the decimal logarithm (8.4%). The spectrum is fitted by the model in a reasonable approximation.

4 Positron fraction and prediction of its fine structure above 200 GeV

It is important that in any successful fit of the data, the fraction of the pulsars electron flux in the total flux of electrons above 200GeV must be high to generate a structure with sufficiently high amplitude. Since a pulsar flux contains negative electrons and positrons in equal fractions, it suggests immediately that the positron fraction must rise rapidly along the energy and must reach values as high as ~ 0.2 and even higher near 400–500 GeV. It is illustrated in Fig. 7, which is generated by the same sets of parameters, as Fig. 6. It is a very important and common prediction of the model; we formulated it already in paper [15]. Now this prediction has been mainly confirmed by the data of experiments up to the energies about 300GeV (see Fig. 7).

Another important prediction of the model is a fine structure that can be seen in the positron fraction curve at highest energies in Fig. 7. It is not an artifact of the model. It is a very common implication of a variation of the pulsars flux, comprised with equal fractions of negative electrons and positrons, in relation to the smooth conventional background, comprised mainly with negative electrons, in the energy range of the observed fine structure 200-600 GeV. Similar fine structure was also predicted, but was not emphasized, in paper [11]. In principle, such a fine structure also could be measured experimentally. However, since the amplitude of the structure in the positron fraction is somewhat less than the fine structure amplitude in the electron spectrum, and since the statistics of positrons is less than statistics of the total electron flux, then the observation of the fine structure in the positron fraction is a more difficult experimental problem than the observation of the fine structure in the total electron spectrum. Also, there is a need for high-resolution measurements of the positron fraction spectrum to observe the phenomenon. Note, that the last AMS-02 data [19] has already included a part of energy region above 200 GeV where the fine structure was predicted, but the data in this region were not high-resolution. There are only two energy bins above 200 GeV in the data of AMS-02: 206–260 GeV and 260–350 GeV [19], and the ATIC's fine structure completely 'sinks' in these two bins. It may be directly seen in Fig. 7. Therefore high-resolution measurements of the positron fraction above 200 GeV are still expected.

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