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SPACE PLASMA

On the Reason for the Kink in the Rigidity Spectra of Cosmic-Ray Protons and Helium Nuclei near 230 GV

V. M. Loznikov, N. S. Erokhin, N. N. Zol'nikova, and L. A. Mikhailovskaya
Space Research Institute, Russian Academy of Sciences, Profsoyuznaya ul. 84/32, Moscow, 117997 Russia
e-mail: loznikov@yandex.ru
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Abstract—A three-component phenomenological model describing the specific features of the spectrum of cosmic-ray protons and helium nuclei in the rigidity range of $30–2 \times 10^5$ GV is proposed. The first component corresponds to the constant background; the second, to the variable "soft" (30–500 GV) heliospheric source; and the third, to the variable "hard" (0.5–200 TV) source located inside a local bubble. The existence and variability of both sources are provided by the corresponding "surfatron accelerators," whose operation requires the presence of an extended region with an almost uniform (in both magnitude and direction) magnetic field, orthogonally (or obliquely) to which electromagnetic waves propagate. The maximum energy to which cosmic rays can be accelerated is determined by the source size. The soft source with a size of ~100 AU is located at the periphery of the heliosphere, behind the front of the solar wind shock wave. The hard source with a size of >0.1 pc is located near the boundary of an interstellar cloud at a distance of ~0.01 pc from the Sun. The presence of a kink in the rigidity spectra of *p* and He near 230 GV is related to the variability of the physical conditions in the acceleration region and depends on the relation between the amplitudes and power-law exponents in the dependences of the background, soft heliospheric source, and hard near galactic source. The ultrarelativistic acceleration of *p* and He by an electromagnetic wave propagating in space plasma across the external magnetic field is numerically analyzed. Conditions for particle trapping by the wave and the dynamics of the particle velocity and momentum components are considered. The calculations show that, in contrast to electrons and positrons (e^+), the trapped protons relatively rapidly escape from the effective potential well and cease to accelerate. Due to this effect, the *p* and He spectra are softer than that of e^+. The possibility that the spectra of accelerated protons deviate from standard power-law dependences due to the surfatron mechanism is discussed.

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1. INTRODUCTION

In this work, we suggest an explanation for the variability of the spectra of cosmic-ray (CR) protons (*p*) and helium nuclei (He) in the rigidity range of $30–2 \times 10^5$ GeV. Special attention is devoted to the variability of *p* and He fluxes in the energy range of >1 TeV.

The PAMELA charged-particle spectrometer [1] installed on the Resurs-DK1 satellite and operating in a wide energy range of 1–1000 GeV detected a singularity (a sharp V-shaped kink) in the *p* and He spectra (measured in 2006–2008) near the rigidity of 230 GV (see Fig. 1).

In the ATIC-2 balloon experiment [2], carried out 3.5 years earlier (in the period of December 2002–January 2003), the *p* and He spectra were measured in the energy range of 50 GeV–30 TeV. In the proton spectrum, which partially overlaps the spectrum measured by the PAMELA spectrometer, one can also see such a singularity. The ATIC-2 spectrum agrees well with the spectrum measured in the BESS-TeV balloon experiment [3] carried out in August, 2002. However, in the BESS-TeV spectrum of helium nuclei, there is no such a singularity. It should be noted that the ATIC-2 and PAMELA spectra coincide only in the energy range of E > 300 GeV and the slope of the ATIC-2 spectrum increases gradually (without a kink) in the range of E > 200 GeV (Fig. 1).

The ATIC-2 spectra of He nuclei in the range of E < 300 GeV agree better with the spectra obtained in the BESS-TeV balloon experiment (08.2002), which is explained by the relatively short time interval between these experiments (about four months). Nevertheless, as will be shown below, agreement between the spectra of He nuclei in the ATIC-2 and PAMELA experiments is also quite satisfactory.

The energy spectra of *p* and He in the energy range of 2.5–250 TeV measured during one month (from December 2004 to January 2005, i.e., 1.5 years earlier than in the PAMELA experiment) in the CREAM balloon experiment [4, 5] unfortunately do not overlap the PAMELA spectra, but well fit the continuation of the PAMELA and BESS-TeV spectra. To illustrate the

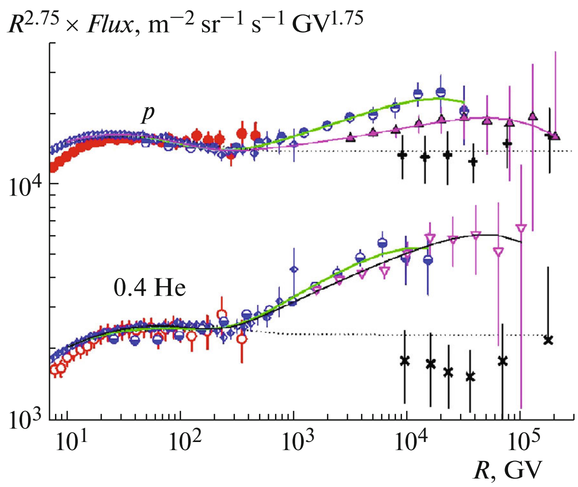

Fig. 1. (Color online) Spectra of p and He (and their approximations) for five experiments: PAMELA (half-closed diamonds) and BESS-TeV (circles) in the rigidity range of <1 TV, as well as ATIC-2 (half-closed circles), CREAM (triangles), and RUNJOB (crosses) in rigidity range of >1 TV. Rigidity R is plotted on abscissa, and differential (per unit rigidity interval) flux multiplied by rigidity to the 2.75th power ($Flux \times R^{2.75}$) is plotted on ordinate.

variability of the spectra in the energy range of $E >$ 1 TeV and demonstrate that the exponent of the background can take a value of ~2.75, we also show in Fig. 1 (on the scale $Flux \times R^{2.75}$) the data from the RUNJOB balloon experiment [5, 6] obtained in the energy range of 10–1000 TeV during ten flights in 1995–1999.

Disagreement between the CR spectra in the energy range of ~10–10^6 GeV measured by different (or identical) instruments in different years has been known for a long time. It is worth recalling some recent explanations of the singularities observed in the spectra and different slopes of the p and He spectra. One hypothesis [4] is that the spectra of CR protons and He nuclei are different because p and He emerge in different kinds of sources or are accelerated in different spatial regions of the same source. For example, CR protons emerge from supernovas (SNs) as a result of explosions of massive stars in the interstellar medium, while CR He and other heavy nuclei arrive from SNs as a result of explosions of massive stars in atmospheres swept out by the stellar winds of ancestor stars.

Another hypothesis [7] supposes that the CRs are accelerated by the shock waves of SN remnants, propagating in the magnetized winds of Wolf–Rayet-type stars or red supergiants. In this case, acceleration in winds issuing from the polar regions of stars yields more rigid spectra than acceleration in winds issuing from equatorial regions. In spite of the smaller fraction of the "polar component," its contribution to the high-energy part of the spectrum is dominant. This hypothesis predicts equal slopes of the spectra at equal rigidities for all nuclei.

A third hypothesis [8] explains the more rigid CR spectra without introducing different sources. This hypothesis assumes that higher energy CRs are generated in the region enriched with helium, i.e., inside a supperbubble. Recall that bubbles and superbubbles (SBs) are large regions (from several tens to several hundred parsecs in size) with a reduced density of the galactic gas formed by hot stellar winds from massive stars in OB associations and shock waves from SN explosions and bounded by sheaths consisting of compressed interstellar gas [9]. The authors of [8] suggest that reduction in the helium content with increasing distance from an SN leads to a more rigid spectrum of He if the CR spectra inside and outside the SN remnant are different; therefore, the resulting spectrum depends substantially on the time evolution of the amount and maximum energy of accelerated CRs.

A fourth hypothesis [10] is based on the traditional Fermi-I acceleration mechanism and the diffusion shock acceleration (DSA) mechanism in SN remnants. Taking into account the similarity between the singularities of the p and He spectra measured by the PAMELA instrument [1], the authors of this hypothesis concluded that CR protons and He nuclei cannot come from independent sources. Therefore, since the DSA mechanism cannot generate spectra with a V-shaped kink in one source, they suppose the existence of two different sources such that the exponents for the hard ($R > 230$ GV) component of the p and He spectra are greater than those for the soft ($R < 230$ GV) component. The authors of [10] explain the higher rigidity of the He spectra compared to that of the p spectra by the additional injection of thermal p and He from the region lying ahead of the shock front.

A fifth hypothesis based on the three-component model [11] assumes that galactic CRs (with energies in the range of 10–10^8 GeV) comprise a mixture of CR fluxes accelerated by shock waves generated by three classes of sources. The first class includes solitary SNs in the interstellar medium, the second class includes SNs in a superbubble, and the third class includes new stars. It is assumed that the most rigid spectra are generated in the second class of sources, whereas the softest ones are generated in the third class. The harder spectra of He (as compared to the p spectra) are explained by different spectral indices and different elemental compositions inherent in different types of sources.

In the present paper, we suggest a hypothesis explaining the variability of the CR spectra in the energy range from 30 to 2×10^5 GeV and the kink near 230 GV by the variability of two different sources (in addition to the constant galactic background) localized in different regions lying relatively close to the Sun.

Earlier, the variability of the CR components (electron, positron, and protons) in the energy range of 10–1000 GeV was explained by the existence of a surfatron [12–14] accelerator at the periphery of the heliosphere [15–17], in the region located between the termination shock of the solar wind and the heliopause (at a distance of ~100 AU from the Sun).

In this work, we use the idea of surfatron acceleration [12–14] to explain the variability of the CR spectra at rigidities of >1 TV and the V-shaped kink in the spectra of CR protons and He nuclei near 230 GV. We assume that the second (harder) variable source is a surfatron accelerator located in the region of a local interstellar cloud (LIC).

By analogy with the generation of electromotive force in a conductor moving across a magnetic field, plasma waves in the course of surfatron acceleration trap and transfer charged particles almost orthogonally to the magnetic field. As a result, an electric field accelerating charge particles arises in the wave frame of reference. Therefore, to confirm our hypothesis, we need direct and/or indirect evidence of the presence of an extended ordered magnetic field and the existence of plasma waves in the acceleration region.

Regardless of the acceleration mechanism, the magnitude of the large-scale magnetic field in the acceleration region should be high enough to confine accelerated particles [18, 19]; i.e., the cyclotron radius of charged particles should not exceed the size of the acceleration region, $L_c = R/B_m$. In this formula, $R \equiv pc/Ze = (T_{\rm kin}/Z)(1 + 2Mc^2/T_{\rm kin})^{1/2}$ is the rigidity, where p is the particle momentum, c is the speed of light, Z is the charge number, e is the proton charge, $T_{\rm kin}$ is the kinetic energy, M is the particle mass, and B_m is the magnitude of the magnetic field. For estimates, it is more convenient to express the size of the acceleration region in astronomic units, L_c [AU] $\approx 0.22(E/Z)/B_m$, where E is the particle energy in GeV and B_m is the magnetic field in μG. This formula implies that, in order to confine charged particle with energies <1 TeV, the magnitude and the characteristic scale length of the ordered magnetic field should be $B_m \approx 1$ μG and ~100 AU, respectively, whereas for particles with energies of about 200 TeV, the characteristic scale length should be ~20 000 AU (i.e., ~0.1 pc). In the neighborhood of the solar system, there is a structure with appropriate dimensions. This is an LIC with a size of at least 3 pc, the boundary of which is at a distance <2000 AU (or <0.01 pc) from the Sun. Such a proximity of the supposed acceleration region to the Sun can provide the observed variability. Then, the question arises of whether there are indications of the existence of an ordered magnetic field in the LIC. Indirect arguments for the existence of such a field are, in particular, hydrodynamical. According to [20], the shape of the outer and inner shock waves and parameter distributions are universal for various astrophysical sources, such as interstellar bubbles, stellar winds around globules, regions of interaction of stellar winds in double systems, etc. If we assume that not only the hydrodynamics, but also the structure of magnetic fields near shock waves, are similar to the structure of the magnetic field at the periphery of the heliosphere, then the conditions in the vicinity of the LIC are suitable for achievenent of surfatron acceleration.

Another indirect argument in favor of the existence of an ordered magnetic field may be the model proposed in [21], which explains the shape and intensity of the IBEX ribbon formed by energetic (~1 keV) neutral atoms and detected by the IBEX satellite. The authors of [21] suggest that, at the boundary of the LIC, at a distance of less than 500–2000 AU from the Sun, there is an intermediate layer (IR) in which hydrogen atoms emerging from the LIC undergo charge exchange with protons in a local bubble located outside the LIC. It is also assumed that the magnetic field ($B_m \approx 4$ μG) between the IR and the heliosphere is ordered and orthogonal to the velocity of neutral hydrogen and helium atoms.

A direct proof of the existence of plasma waves may be radio-frequency emission at a plasma frequency of ~2.6 kHz detected by the PWS instrument onboard the Voyager-1 spacecraft after crossing the heliopause [22, 23]. Although particular details of the mechanism for the generation of 2- to 3-kHz emission are still under discussion [24], it is generally accepted that radio-frequency emission near the electron plasma frequency, f_{pe} [Hz] $= [n_e e^2/(\pi m_e)]^{1/2} \approx 8977(n_e\,[\mathrm{cm}^{-3}])^{1/2}$, and/or at its second harmonic, $2f_{pe}$, is generated as a result of nonlinear plasma wave conversion. This emission propagates from the generation region downward the gradient of the plasma frequency f_{pe} and can be used as a diagnostic tool for determining the plasma density in this region.

Acceleration of superthermal electrons by shock waves results in the generation of electron beams, which in turn excite Langmuir waves due to beam–plasma instability, [24, 25]. More exactly, when the plasma is in a magnetic field, upper hybrid plasma oscillations are generated, the frequency of which, $f_{\rm UH} = [f_{pe}^2 + f_{ce}^2]^{1/2}$, is close to the electron plasma frequency f_{pe}, because the cyclotron frequency f_{ce} [Hz] $= eB/(2\pi m_e c) \approx 2.8B$ [μG] is much lower than f_{pe}.

2. MODEL OF THE SPECTRUM

Thus, we propose a three-component phenomenological model describing the observed spectra of CR protons and He nuclei. According to this model, the CR flux for the jth component ($j = p$, He) is $F_{(j)} = F_{\mathrm{B}(j)} + F_{\mathrm{SH}(j)} + F_{\mathrm{SG}(j)}$. The first component, $F_{\mathrm{B}(j)} = B_{(j)}R^{-\beta_{(j)}}$, corresponds to the power-law background with the spectral index $\beta_{(j)}$. The second component,

Table

j	$\alpha_{H(j)}$	$\alpha_{G(j)}$	$R_{CH(j)}$, GV	$R_{CG(j)}$, GV	χ^2/d.o.f.
p	2.54 ± 0.39	2.23 ± 0.18	80 ± 42	31700 ± 14600.	0.35
He	2.42 ± 0.89	2.07 ± 0.43	107 ± 143	11600 ± 8410	1.21

$F_{SH(j)} = S_{H(j)}R^{-\alpha_{H(j)}}\exp(-R/R_{CH(j)})$, with the slope index $\alpha_{H(j)}$ and truncation at the rigidity $R_{CH(j)} <$ 1 TV corresponds to the "soft" power-law source located at the periphery of the heliosphere. The third component, $F_{SG(j)} = S_{G(j)}R^{-\alpha_{G(j)}}\exp(-R/R_{CG(j)})$, with the slope index $\alpha_{G(j)}$ and truncation at the rigidity $R_{CG(j)} <$ 100 TV corresponds to the "hard" galactic source located near the LIC boundary.

The values of the slope indices $\alpha_{H(j)}$ and $\alpha_{G(j)}$ and truncation parameters $R_{CH(j)}$ and $R_{CG(j)}$ obtained by approximating the PAMELA and ATIC-2 data are given in the table.

We see that, although the times of the PAMELA and ATIC-2 experiments differ by more than 3 years, the approximation is quite satisfactory.

It also follows from the experimental data that the characteristic variability time of the soft source is several months, while that of the hard source is several years. Such characteristic times may correspond to a soft heliospheric source located behind the termination shock and a hard galactic source with a size of >0.1 pc located near the LIC boundary at a distance of ~0.01 pc from the Sun, respectively. CRs can escape from the acceleration region as a result of instabilities and then propagate diffusively toward the Earth.

3. NUMERICAL MODEL OF SURFATRON ACCELERATION OF He NUCLEI BY AN ELECTROMAGNETIC WAVE IN SPACE PLASMA

Let us consider the process of surfatron acceleration of He nuclei by an electromagnetic wave in the space plasma on the basis of numerical calculations. For He nuclei, we use relativistic equations with a uniform magnetic field directed along the z axis. A wave with amplitude E_0 propagates along the x axis. The main component of the wave electric field is $E_x = E_0\cos\Psi$, where $\Psi = \omega t - kx$, with ω and k being the wave frequency and wavenumber, respectively. Surfatron acceleration takes place if $v_{ph} = \omega/k < c$. This condition is satisfied at the upper hybrid frequency. Let us introduce the parameters $\sigma = eE_0/m_ec\omega$ and $\beta_p = v_{ph}/c$, the dimensionless coordinate $\xi = \omega x/c$, and dimensionless time $s = \omega t$. For helium nuclei with an electric charge Ze ($Z = 2$) and a mass M, the relativistic equations of motion have the form

$$\frac{d(\gamma\beta_x)}{ds} = \varepsilon^2\sigma\cos\Psi + \varepsilon^2 u\beta_y,$$
$$\frac{d(\gamma\beta_y)}{ds} = -\varepsilon^2 u\beta_x, \quad \frac{d(\gamma\beta_z)}{ds} = 0, \tag{1}$$
$$\frac{d\gamma}{ds} = \varepsilon^2\sigma\beta_x\cos\Psi.$$

Here, $\varepsilon = (Zm_e/M)^{1/2}$ and $u = \omega_{ce}/\omega < 1$, where ω_{ce} is the cyclotron frequency of nonrelativistic plasma electrons. It should be noted that, for $u^2 \ll 1$, we have $\omega \approx \omega_{pe}$. Equations (1) have two integrals of motion,

$$h = \gamma\beta_z = \text{const},$$
$$J = \gamma\beta_y + \varepsilon^2 u\beta_p(s - \Psi) = \text{const}. \tag{2}$$

Since $\varepsilon^2 \ll 1$, for the reliability of numerical calculations, we introduce the slow dimensionless time $\tau = \varepsilon s$. As a result, from set of equations (1), taking into account constants (2), we obtain the following nonlinear equation for the wave phase on the path of a helium nucleus:

$$\frac{d^2\Psi}{d\tau^2} + \frac{\sigma\beta_x}{\gamma\beta_p}\cos\Psi + \frac{u\beta_y}{\gamma^2\beta_p} = 0. \tag{3}$$

The dimensionless velocity of a helium nucleus along the wave front is $\beta_y = [J + \varepsilon u\beta_p(\varepsilon\Psi - \tau)]/\gamma$, and its relativistic factor γ is

$$\gamma = \left\{\frac{1 + h^2 + [J + \varepsilon u\beta_p(\varepsilon\Psi - \tau)]^2}{1 - \beta_p^2(1 - \varepsilon d\Psi/d\tau)^2}\right\}^{1/2}. \tag{4}$$

Equation (3) was solved numerically with the initial conditions $\Psi(0) = \Psi_0$ and $\varepsilon d\Psi/d\tau|_{t=0} = a$.

Constants h and J are found from the initial values of the velocity and momentum components of a helium nucleus. The strong surfatron acceleration of He nuclei by an electromagnet wave in space plasma were calculated numerically, in particular, for the following set of initial parameters: $u = 0.3$, $\beta_p = 0.8$, $h = 10$, $g(0) = \gamma(0)\beta_y(0) = -10$, $\sigma = 1.5\sigma_c$, $\sigma_c = u\gamma_p$, and $a = 0$. The phase Ψ_0 was assumed to be in the range from –3.1 to 3.1. The calculations were performed in the time interval $\tau < 3 \times 10^4$. The results of calculations show that, for the initial phases in the range of $\Psi_0 =$ –2.2 to 0.6, a particle is immediately trapped by the wave into the surfatron acceleration mode. For other phases in the time interval $\tau < 3 \times 10^4$, the particles are

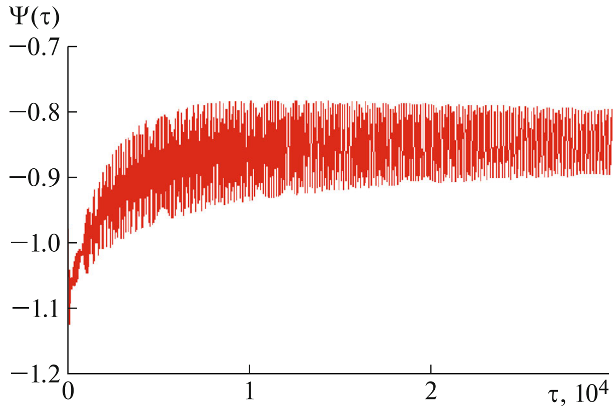

Fig. 2. (Color online) Time evolution of wave phase on path of trapped helium nucleus.

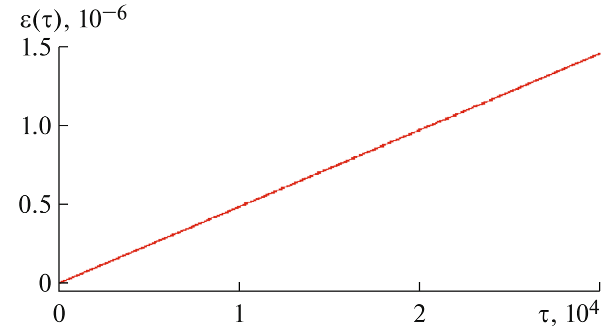

Fig. 3. (Color online) Time evolution of displacement of trapped particle in the wave propagation direction.

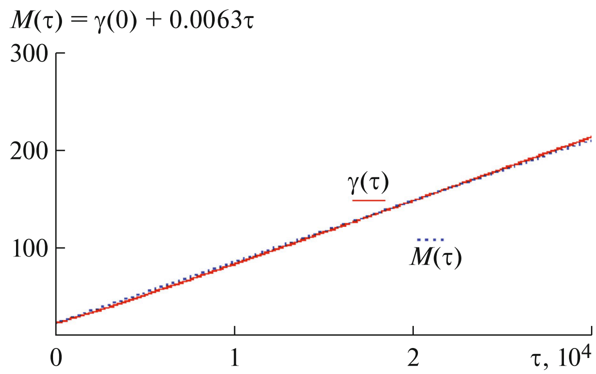

Fig. 4. (Color online) Time evolution of relativistic factor of trapped particle and its analytical approximation $M(\tau)$.

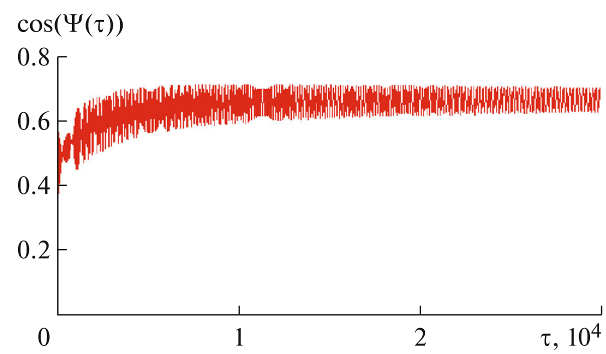

Fig. 5. (Color online) Function $\cos\Psi(\tau)$.

not trapped by the wave, but for some Ψ_0 values from this range, e.g., for $\Psi_0 = 0.7$, 0.8, and 0.9, a particle is confined in the effective potential well over time intervals of 1290, 603, and 349, respectively, which are too short for the particle energy to increase significantly. A typical profile of the wave phase along the path of a trapped particle, $\Psi(\tau)$, is shown in Fig. 2. As time elapses, the phase tends to a value Ψ_f determined by the position of the bottom of the effective potential well, which is found from the condition $\cos\Psi_f = \sigma_c/\sigma$. Figure 3 shows the profile of displacement of a trapped particle in the wave propagation direction. This is an almost straight line corresponding to the approximation $\xi \approx \beta_p\tau/\varepsilon$. Figure 4 shows the time evolution of the relativistic factor of a trapped particle and its analytical approximation $M(\tau)$. As we see, the trapped particle is accelerated so that its energy increases at an almost constant rate. If the initial value $\gamma(0)$ is 23.629, then at time $\tau = 3 \times 10^4$, we have $\gamma \approx 215.34$, which corresponds to a highly relativistic energy of a helium nucleus of 806 GeV. For an acceleration length of 0.1 pc, the relativistic factor (for the above value of the initial parameters) is $\gamma \approx 0.98 \times 10^6$, i.e., the energy of a helium nucleus is $\approx 3.68 \times 10^{15}$ eV. The time of such acceleration is $\delta\tau \approx 1.37 \times 10^8$. The time evolution of the function $\cos\Psi(\tau)$, which determines the interaction of a particle with the wave, is shown in Fig. 5. For a sufficiently large computation time, one can see an increase in the characteristic oscillation time accompanied by a slow decrease in the amplitude of $\Psi(\tau)$ oscillations. Figure 6 shows the trajectories of the imaging point on the plane of the transverse (with respect to the magnetic field) velocity components β_x and β_y of the trapped particle in the time interval $\tau < 3 \times 10^4$. The trajectory corresponds to a spiral approaching a singular point of the type of stable focus located at the bottom of the effective potential well for the trapped particle. Finally, Fig. 7 shows the time evolution of the transverse components of the momentum of the trapped particle, $g_x = \gamma\beta_x$ and $g_y = \gamma\beta_y$. With good accuracy, they can be approximated by straight lines. This is quite natural, because at large energies, the velocity components of the trapped par-

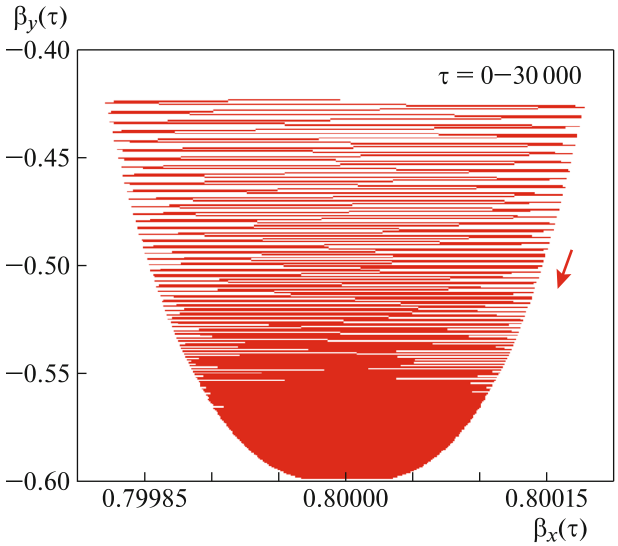

Fig. 6. (Color online) Trajectory of imaging point in plane of transverse (with respect to magnetic field) components of trapped particle velocity. Arrow indicates direction of motion.

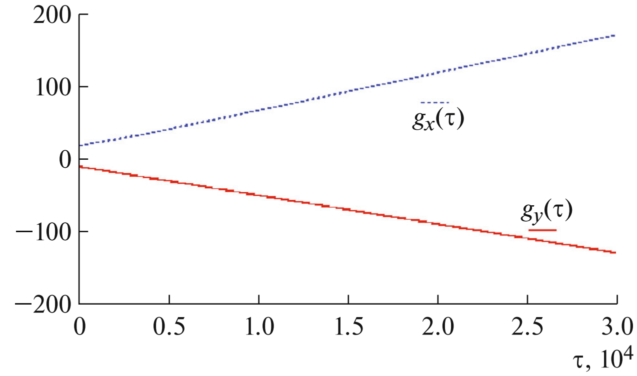

Fig. 7. (Color online) Time evolution of transverse components of momentum of trapped particle, $g_x = \gamma\beta_x$ and $g_y = \gamma\beta_y$.

ticle asymptotically approach values of $\beta_x \approx \beta_p$ and $\beta_y \approx -1/\gamma_p$.

Thus, the results of numerical calculations show that, under Cherenkov resonance conditions, He nuclei with favorable initial phases are trapped into the regime of ultrarelativistic acceleration. It should be noted that, at relativistic initial energies of particles, there is only one relatively wide range of phases favorable for particle trapping, which makes up 44.6% of the wavelength. In a future study, we plan to examine this in more detail for strongly relativistic initial energies of He nuclei such that $\gamma(0) \geqslant 10^3$.

4. DISCUSSION

In this work, we study the variability of the spectra of CR protons and He nuclei in the rigidity range of 30–2 × 10^5 GV. The explanation for the variability of the spectrum of CR protons in the relatively soft energy range (<1 TeV) was the subject of our previous work [17]. In the present work, we concentrated on the variability of the spectra of CR protons and He nuclei in the energy range of >1 TeV.

It was shown in [10] that, if particles were accelerated via the DSA mechanism (the traditional Fermi-I mechanism), then the p and He spectra would have the same slope indices. However, the actual indices are different. Thus, the DSA mechanism can explain neither the variability nor the difference in the slope indices of the energy spectra of p and He.

Multicomponent models have already been proposed to explain the CR spectra. In particular, in [11], a model with three types of sources was proposed to describe the CR spectrum in the energy range of from 100 GeV to 100 PeV. However, although that model describes fairly well selected experimental data in the energy range of $E > 200$ GeV, it fails to explain the variability of the entire set of CR spectra in this range or at $E < 200$ GeV. None of the statistical mechanisms can explain the variability of CR spectra on a time scale on the order of several months or years. Precisely this has stimulated our search for an alternative acceleration mechanism. It is clear that the sources responsible for variability of the CR spectra should be located quite close to the Earth and result in fast generation of CR.

In our previous works [15–17], the variability of CR spectra in the energy range of 10–500 GeV was explained by the existence of an additional source (a charged particle surfatron accelerator) at the periphery of the heliosphere.

In this work, the variability of the observed p and He spectra in the rigidity range of >1 TV is explained by the existence of another surfatron accelerator located in the vicinity of the solar system, near the LIC boundary. As was mentioned in the Introduction, there are reasons to assume that the structure of the magnetic field near the LIC boundary is appropriate for confinement of charged particles. For the surfatron mechanism to operate, plasma waves with a phase velocity $\omega/k < c$ are needed. What can the source of such waves be? It can be assumed that the most powerful source of such waves are shock waves [24, 25] generated in the collision of two clouds—the LIC and G-complex located along the sunward boundary of the LIC. In the proposed model, the three-component flux $F_{(j)} = F_{B(j)} + F_{SH(j)} + F_{SG(j)}$ for each component ($j = p$, He) is assumed to be the sum of a constant background $F_{B(j)}$ and two variable power-law surfatron sources $F_{SH(j)}$ and $F_{SG(j)}$. By choosing the appropriate values of the truncation parameters ($R_{CH(j)}$ and $R_{CG(j)}$), slope indices ($\alpha_{H(j)}$ and $\alpha_{G(j)}$), and amplitudes ($S_{H(j)}$ and $S_{G(j)}$) for each CR component, we can describe and explain the occurrence of a kink (or a smooth inflexion) in the energy spectra of p and He or the absence of such a singularity.

The values of the truncation parameters ($R_{CH(j)}$ and $R_{CG(j)}$) differ substantially: $R_{CH(j)}$ ~ 100 GV and $R_{CG(j)} \geqslant 10$ TV. This is related to the different dimensions of the regions in which the surfatron accelerators responsible for the generation of the variable CR components operate: the heliospheric accelerator, $F_{SH(j)}$, located between the termination shock and the heliopause with a radius of ~100–200 AU, and the near galactic accelerator, $F_{SG(j)}$, located near the LIC situated at a distance of ~2×10^4 AU from the Sun. Here, we present only a qualitative explanation for the difference in the exponents of the spectra of CR protons and He nuclei. Quantitative estimates will be the subject of our future study. The condition for the indices $\alpha_{G(He)} < \alpha_{G(p)}$ arises because the same e.m.f. (in the wave frame of reference) more efficiently accelerates He nuclei (the charge of which is twice as large as the proton charge), while charged particles with a lower mass (protons) are more efficiently trapped by the plasma wave. The presence of a kink at the same p and He rigidity indicates that all charged particles are accelerated by waves in the magnetic field, as is required for the operation of the surfatron mechanism in space plasma.

5. CONCLUSIONS

In this work, a three-component phenomenological model has been proposed to describe the singularities of the spectra of CR protons and He nuclei in the rigidity range of 30–2×10^5 GV. The first component of the spectra corresponds to the constant background; the second, to a variable soft (30–500 GV) heliospheric source; and the third, to a variable hard (0.5–200 TV) galactic source located inside a local bubble. The existence and variability of both sources are provided by the corresponding surfatron accelerators, whose operation requires the presence of an extended region with an almost uniform (in both the magnitude and direction) magnetic field orthogonally (or obliquely) to which plasma waves propagate. The size of each source determines the maximum energy to which CRs can be accelerated in this sources. The soft source with a size of ~100 AU is located at the periphery of the heliosphere, behind the shock wave of the solar wind, whereas the hard source with a size of >0.1 pc is located near the boundary of a local interstellar cloud at a distance on the order of 0.01 pc from the Sun. Estimates obtained from numerical calculations have shown that ultrarelativistic surfatron acceleration of charged particles (electrons, positrons, protons, He nuclei, etc.) up to energies of 10^{10}–10^{16} eV or more can occur in a relatively calm space plasma. The components of the momenta of charged particles with highly different masses have similar dynamics. It follows from the calculations that there are optimal conditions for particle acceleration by electromagnetic waves in space plasma.

The presence of a kink in the rigidity spectra of p and He near 230 GV is an episodic phenomenon related to variability of the physical conditions in the acceleration region. It depends on the relation between the amplitudes and power-law exponents of the background for the soft heliospheric source and the hard near galactic source. The higher rigidity of the spectrum of CR He nuclei compared to that of CR protons is qualitatively explained by the fact that surfatron acceleration is more efficient for particles with a larger charge, while trapping of charged particles by the plasma wave is more efficient for particles with a smaller mass.

The proposed hypothesis on the surfatron nature of variable sources is confirmed by the results of [26], which show that, to within measurement errors, the rigidity at which the spectra of different nuclei (H, He, C, O, Ne, Mg, Si, and Fe) have a V-shaped kink is nearly the same.

The variability of CR spectra is also confirmed by the results of the recent AMS-02 experiment [27] performed over 1.5 years (since May 19, 2011, to December 10, 2012), according to which no appreciable singularity near 230 GV was observed. Therefore, about 3 years after the PAMELA experiment [1] (carried out in 2006–2008), the energy spectrum of p and He has changed substantially.

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