Astrospheres and Cosmic Rays

A. Struminsky$^{1,2}$ and A. Sadovski$^{1,3}$

1 Space Research Institute, 84/32 Profsoyuznaya str., Moscow, 117997, Russia
2 Moscow Institute of Physics and Technology, 9 Institutskiy per., Dolgoprudny, Moscow Region, 141701, Russia
3 National Research University Higher School of Economics, 20 Myasnitskaya ulitsa, Moscow, 101000, Russia
E-mail: asadovsk@iki.rssi.ru

Abstract. Ionization plays a key role in the formation of stars, planets and planetary atmospheres. Cosmic rays (CR) are the main source of ionization, therefore it is important to estimate fluxes of galactic and stellar cosmic rays (GCR and SCR) for different stages of evolution of stars and planetary systems. Radiation conditions on exoplanets might be important for the origin and development of life. We present a review of the current state of knowledge of astrospheres and their interactions with GCR and SCR. We pay special attention to estimates of radiation conditions near exoplanets recently discovered in a habitable zone of their hosting stars.

1. Introduction—astrophysics of low energy CR

Traditionally the astrophysics of cosmic rays (OG section of CR conferences) considers CR above 10 GeV since CR of lower energies have their flux modulated in the heliosphere by the solar magnetic field and solar wind, some part of low CR rays are accelerated inside the heliosphere in solar flares or by shock waves driven by Coronal Mass Ejections (CME). Problems of low energy CR physics were discussed at SH (Sun and Heliosphere) section of CR conferences [1]. Recent years have seen the birth of low energy CR astrophysics, which is tightly connected to astrochemistry, radioastronomy and solar physics. At present, the astrophysics of low energy CR consider CR in three locations—molecular clouds, protoplanetary discs and astrospheres.

The cosmic-rays dominate in the ionization and heating of the interstellar medium (ISM). Recent measurements, made beyond the heliopause by the Voyager I spacecraft, have provided data of lower energy cosmic-ray protons and electrons down to energies about 3 MeV [2]. Nevertheless, it remains unclear whether the cosmic-ray fluxes reach their unmodulated values even at the current location of Voyager I. However, the ionization cross-sections for atomic and molecular hydrogen have a maximum at 0.01 MeV, so an extrapolation of unobserved energies is still required to determine the implied cosmic ray ionisation rate, which remains quite uncertain even in the solar neighbourhood [3].

Remarkably, the spectra of both proton and electron CRs in the local interstellar medium (ISM)— at least down to particle energy of a few MeVs— are now known with some confidence thanks to the recent data collected by the Voyager probe at large distances from the Sun [2]. Whether or not such spectra are representative of the average Galactic spectra, especially for MeV CRs, is still not clear. However, the analysis of gamma rays from Molecular clouds (e.g., [4]) seems to indicate that at least the spectrum of proton CRs of energy above a few GeV is
quite homogeneous in our Galaxy. The intensity of CRs in the local ISM as revealed by Voyager measurements is too weak to explain the level of ionization rate observed in clouds. Possible solutions to this problem include the presence of another source of ionization or a non-uniform intensity of low energy CRs throughout the Galaxy [5].

One of the possible sources of CR was suggested by [6]. They hypothesized the existence of an acceleration mechanism for both cosmic-ray protons and electrons through the diffusive shock acceleration near protostars. This mechanism may explain the high ionisation rate and the synchrotron emission observed. Also, such internal sources of energetic particles should have a strong influence on the ionisation of the protostellar disc, on star and planet formation processes, and on the formation of pre-biotic molecules [6].

As in the solar system where solar wind can inhibit the CRs propagation, also stellar winds can modulate CR spectra within the circumstellar environment and subsequently into the disk. In [7] a two-dimensional protoplanetary disk model of a T-Tauri star system was constructed and ionization from stellar and interstellar far ultraviolet, stellar X-ray photons, and CRs was found. According to their results stellar winds can conform a heliosphere-like analog, i.e., using the term of the authors T-Tauriosphere decreases CR ionization rates by several orders of magnitude at low to moderate CR energies (∼1 GeV). The implications of a diminished CR ionization rate on the physics of the disk was performed by investigation of the magnetorotational instability: if winds are so efficient at CR modulation, than the major source of ionization would be short-lived radionuclides [7]. However, the authors didn’t consider the stellar CR.

The Chandra X-ray satellite observed the large flares on T Tauri stars which can give a significant amount of energetic particles and recently the Herschel Space Observatory provided evidence of their possible contribution to the disk ionization of young stars. Authors of [8] modeled ionization of stellar energetic particles in protoplanetary disks around T Tauri stars using a particle energy distribution derived from solar flare observations and an enhanced stellar particle flux proposed for T Tauri stars. They have shown that stellar energetic particles can be an important ionization agent for disk chemistry.

Test-particle numerical simulations of energetic protons propagating into a realistic T Tauri stellar wind have shown that in the energy range 0.1–10 GeV they are consistent with expectations from Chandra and the Herschel Space Observatory observations [9]. Also in [9] was found that the disk ionization is dominated by X-rays over much of its area, except for some narrow regions where particles are channeled by the turbulent magnetic field, in contrast with a previous theoretical study.

Moreover, a proper description of particle transport is essential to compute the ionization rate since the electron and positron differential fluxes depend sensitively on the fluxes of both protons and photons [10]. Their results show that the CR ionization rate in high-density environments, such as the inner parts of collapsing molecular clouds or the mid-plane of circumstellar disks, is higher than previously assumed.

Exoplanet discovery gives a great impetus to investigate both habitability conditions and possible habitable planets. However, from the investigation of the Earth environment it seems to be clear that the radiation environment should have a great influence on any planet and its atmosphere. Despite their importance, CRs and their influence on radiation conditions near planets have dropped out of the discussion, and, perhaps, only one group actively investigates the influence of CRs on exoplanets (see for example [11]). The influence of Galactic cosmic rays (GCRs) on planets depend on planetary magnetosphere and atmosphere and has been considered in several papers (see, e.g., [12, 13]). In paper [14] the influence of CRs on the atmosphere of an Earth-like exoplanet was investigated and it was suggested that the GCR flux might be considered as an isotropic and nearly constant one. However the authors did not consider GCR modulation.

Such problems are similar to the investigations of archean Earth in the young Sun
environment. For example, the quantitative model developed in [15] demonstrated that a change of the interstellar medium surrounding the heliosphere triggers significant changes of planetary environments caused by enhanced fluxes of neutral atoms as well as by increased cosmic ray fluxes for $10^4$–$10^6$ years. In paper [16] the 3D MHD models for solar wind and a 2D model for CGR transferring near archean Earth were used. It was showed that the GCR flux has greatly reduced with comparison to present conditions. The reason mainly being the shorter solar rotation period and tighter winding of the Parker spiral, and to the different surface distribution of the more active solar magnetic field.

In contrast to Galactic cosmic rays, the detection (or separation from the total flux) of SCR is impossible far from the parent star, and because of this they are the “stepsons” of CR physics usually mentioned as a possible CR component approximately once every ten years [17, 18, 19, 20, 21, 22, 23]. Nevertheless, stellar CRs are considered an important factor of space weather in the habitable zone of a star in many papers [24, 25, 23]. Unfortunately, the spectrum of stellar CRs cannot be determined and the well known spectra of solar CRs [25, 24] are used to model stellar CRs. Another approach is based on general physical laws and also uses the solar–stellar analogy, but without using near-Earth solar CR observations [23].

Here we review methods proposed in our previous papers [23, 26, 27] showing the Sun-stellar similarities and scaling of stellar parameters which allows us to obtain the correct estimates for different stars by the order-of-magnitude. The previous paper was devoted to the Proxima Centauri system [26] and for TRAPPIST-1 system [27]. Below we present some our results for TRAPPIST-1 and new unpublished estimates for $\sigma$ Ori E. The next section is devoted to the methods using for calculations and their discussion. The section 3 presents results for TRAPPIST and $\sigma$ Ori E.

2. Methods
2.1. Stellar wind and atmosphere
Solar wind velocity, particle density, magnetic field and dimension of the heliosphere are essential parameters for propagation and modulation of CR observed near the Earth. Analogous parameters of stellar wind and astrosphere would be important for CR near exoplanets of some chosen star.

For the stellar wind velocity, we use the Parker’s model [28], which depends only on the coronal temperature and star radius and is universal for any star system. For a given coronal temperature $T_e$ we may estimate the sound speed $u_{cr} = (2k_B T_e/m_p)^{-1/2}$ and critical distance, where the wind speed became equal to the sound speed, $r_{cr} = G M_* / u_{cr}$ (here $M_*$ is a star mass, $G$ is the gravitational constant). The stellar wind speed for the distance much larger than critical may be estimated as $V_{SW} = u_{cr} \log(r/r_{cr})$.

We may get a coronal temperature from X-ray observations of a particular star or may use estimate of a maximal possible value of the coronal temperature

$$T_{\text{cor}}^{\text{max}} = \frac{G M_* m_p}{4 k R_*} \left(\sqrt{3} - 1\right)$$

determined by the condition that a radius of critical point is equal to the stellar radius plus the coronal height

$$H_{\text{cor}} = \frac{2 k T_{\text{cor}} m_p R_*^2}{G M_*}.$$ 

Here $R_*$ is the star’s radius.

The number density of stellar wind may be estimated from thermal coronal loss. Let us suppose that the heat flux from corona is $Q = -(8\pi/7) R_* k(T_e) T_e$, where $k(T_e) = 6 \times 10^{-8} T_e^{5/2}$ erg · cm$^{-1}$ × s$^{-1}$ · K$^{-1}$ is the thermal conductivity coefficient for fully ionized
gas. Assuming that all the heat flux \( Q \) goes for the coronal spherical symmetrical expansion, we find that
\[
Q \approx 4\pi r^2 m_p \frac{N(r)V_{SW}}{2} (V_{SW}^2 + V_{esc}^2),
\]
where \( V_{esc} = (2GM_*/R_*)^{1/2} \) is the escape velocity) and stellar wind number density \( N \) at some distance \( r \) is
\[
N(r) = \frac{48\pi}{7} R_*^{10^{-6}T_7^{7/2} (V_{SW}^2 + V_{esc}^2)}.
\]
Also now it is possible to find the mass loss rate \( M_r = 4\pi r^2 N m_p V_{SW} \) and the astrosphere radius
\[
R_{as} = R \sqrt{\frac{m_p N V_{SW}^2}{P_{ISM}}},
\]
where \( P_{ISM} = 1 \text{ eV/cm}^3 \) is the pressure of interstellar medium.

For estimates of the magnetic field strength in some point of the atmosphere we may use the Parker spiral. From the magnetic flux conservation follows \( B(r) = B_* (r_*/r)^2 \), where \( B_* \) is the stellar magnetic field at photospheric level. The radius of the first turn of Parker spiral equals to \( r_1 = V_{SW}T(\varphi/2\pi) \), where \( T \) is the stellar rotation period.

2.2. CR modulation
According to [29] a modulated flux of galactic cosmic rays is
\[
j_0(\eta) = j_\infty(\eta) \exp \left\{ -\frac{12V_{SW} (r_1 - r_2) l Z^2 e^2 B^2 (\eta + 1)}{\pi^2 m^2 c^5 \left[\eta(\eta + 2)\right]^{3/2}} \right\},
\]
Where \( \eta \) is a ratio of kinetic energy to the rest particle energy, \( Ze \) is a particle charge, \( m \) is the particle mass, \( l \) is a scale of magnetic field fluctuations (\( l = 2 \times 10^6 \) km for the solar wind), \( (r_1 - r_2) \) is a dimension of modulation shell. In our estimates we assume that a dimension of modulation shell is a difference between radius of point of interest and a radius of first Parker turn. In this case a radius of atmosphere should be greater than the radius of the first Parker turn and the planet orbit should be within the first turn. Therefore to estimate CR modulation near exoplanets we need to know the magnetic field strength and the rotation period from observations of the hosting star.

2.3. Stellar cosmic rays
To estimate the SCR influence let us assume that in stellar flares, the mechanism of proton acceleration is the same as in solar flares and that the main building blocks in star and solar coronas are magnetic loops [23].

Our main suggestion is that in the stable loop magnetic field energy should be in equipartition with thermal plasma energy. From pressure balance \( B_0^2 / 8\pi = n kT = G m_p M_* H/R_*^2 \) assuming the mean free path \( H = (n\sigma_T)^{-1} \) (where \( \sigma_T \) is the Thompson scattering cross-section) we find an estimate of the photospheric magnetic field in the form
\[
B_0 = \frac{1}{R_*} \sqrt{\frac{8\pi G m_p M_*}{\sigma_T}}.
\]

Balona [30] showed that the characteristic scale of an active region is about ten percent of star radius, \( L = \alpha R \), magnetic field over an active region is about one tenth of photospheric
\( B = \beta B_0 \). Here coefficients \( \alpha \beta < 1 \). Using these parameters, we can estimate the flare energy as

\[
E_{fl} = \frac{B^2 L^3}{8\pi} = 2.3 \times 10^{37} \alpha^3 \beta^2 \left( \frac{R}{R_\odot} \right)^2 \left( \frac{M}{M_\odot} \right).
\]

In big solar flares approximately 10% of flare energy is the energy of proton acceleration. Assuming similar processes for the stars we estimate amount of accelerated protons with an average energy \( E_p \) as

\[
N \approx \frac{0.1 E_{fl}}{E_p}.
\]

The electric field over an active region is \( E = uB/c \), where \( u \) is velocity of reconnection, and the maximum energy of protons accelerated in flares would be \( E_{max} = (\alpha \beta/c)uB_0R_\ast \).

The largest fluxes of solar protons \( j_{max} \) observed near the Earth correspond to the arrival of strong magnetic field disturbances and \( j_{max} = F_{max}/(2\pi \tau) \), where \( \tau = r/V_{SW} \) is a propagation time of solar wind disturbances to 1 AU. Let us assume a similar value for stellar cosmic rays, i.e., assume that convection plays a main role in the propagation of stellar CR for strong magnetic field. Note that the solar magnetic field is rather weak in comparison with the magnetic field of several tens to several thousand Gauss observed at magnetic active stars. Considering that stellar CR propagate within spatial angle of \( 60 \times 60 \) degrees we will get fluencies \( F = 9N/\pi r^2 \) and maximal intensities \( j_{max} = F/(2\pi \tau) \), which might be observed at distance \( r \) in the astrosphere.

2.4. Discussion of methods

According to the dynamo theory O–B, A stars have not developed convective zone, as opposed to F–M stars and, therefore, they should not have a magnetic field. If there are no magnetic fields, then we would see an absence of stellar activity, flares, hot corona and hot stellar wind. However magnetic fields [31, 32], X-ray emission (see [33] and references therein) and flares [34] are observed at O–B stars, flares [35] and stellar spots [36] are observed at A-stars. The nature of magnetic fields is still unknown [37], X-ray emission is described by shock waves propagating in cold stellar wind [38] and stellar flares are attributed to an invisible cold companion [34, 39, 40] or wind-shock X-ray emission [34]. We don’t discuss here the magnetic field nature but we assume that presence of rather strong magnetic fields supposes that magnetic structures like arcs and filaments could be formed at O–B, A stars, then we may discuss expanding hot coronas (stellar wind) and their X-ray emission, stellar flares, as well as make estimates using solar-stellar analogous [26].

3. Results

3.1. Estimates for TRAPPIST 1

In the year 2016 the planetary system of TRAPPIST-1 with 7 exoplanets was discovered, four of them are in a possible habitable zone [41]. TRAPPIST-1 is an M8 star at a distance of 10 light years, its parameters are \( M = (0.089 \pm 0.006)M_\odot \), radius \( R = (0.121 \pm 0.003)R_\odot \), effective temperature \( T = 2516 \) K. The rotation period is \( P_{rot} = 3.295 \pm 0.003 \) days [42]. The TRAPPIST-1 star has a hot corona with a ratio of X-ray to bolometric luminosity \( L_x/L_{bol} = (2-4) \times 10^{-4} \) [43], i.e., should have a hot stellar wind similar to the solar wind. Its flare activity was observed by the MOST satellite [42] a frequency of flares with energy \( \sim 10^{33} \) erg is \( f = 1.2 \times 10^{-7} \) s\(^{-1}\). The measured average magnetic field was estimated as 600 G [44], but it is too weak of a source to get ZDI magnetic field maps by using modern instruments. In this paper we will not discuss the possibility of generating such a large field, which is doubtful.

In our recent paper [27] we presented our view on radiation conditions in the TRAPPIST 1 system. Here we show some of our estimates for TRAPPIST 1d only, one of four exoplanets in the habitable zone.

Modelling characteristic values for stellar wind of TRAPPIST 1 are shown in Tab. 1 for different values of the coronal temperature.
Table 1. Stellar wind parameters for the TRAPPIST-1 d ($r_d = 0.0214$ AU)

| $T$, MK | $Q$, erg/s | $n_{SW}$, cm$^{-3}$ | $u_{cr}$, km/s | $r_{cr}/R_*$ | $V_{SW}$, km/s | $r_{Park}$, AU | $R_{AS}$, AU |
|---------|------------|-------------------|---------------|-------------|--------------|-------------|-------------|
| 1       | $1.813 \times 10^{26}$ | 1614              | 131           | 4.0         | 294/366      | 0.6         | 61.5        |
| 2       | $2.051 \times 10^{27}$ | 6267              | 186           | 2.0         | 545/647      | 1           | 224         |
| 3       | $8.480 \times 10^{27}$ | 12510             | 228           | 1.4         | 760/884      | 1.5         | 442         |
| 4       | $2.321 \times 10^{28}$ | 19710             | 263           | 1.0         | 953/1097     | 1.8         | 696         |

Figure 1. The dependence of CR modulation for TRAPPIST 1d for different values of stellar magnetic field and stellar wind velocity 545 km/s ($T_{cor} = 2$ MK)

Figure 1 illustrates a possible effect of GCR modulation for hypothetical values of TRAPPIST 1d magnetic field of 1–600 G and coronal temperatures of 2 MK. This value of coronal temperature corresponds to the solar coronal temperature and is about twice as small as the maximum possible temperature for TRAPPIST 1 corona. From Fig. 1 it is clear, that CR with energies less 1 TeV should be swept out from the astrosphere in a case of magnetic field $> 300$ G. Moreover as $R_{AS} \gg r_1$ the real modulation GCR will be greater. However it is possible, that the real magnetic fields will be much smaller than measured. The modulation effects even for 1 G are more than an order of magnitude higher than for the Earth (Fig. 1).

Assuming the following parameters of an active region: $L = \alpha R = \alpha 8.5 \times 10^9$ cm, $B = \beta B_0 = 3000 \beta$ G, $V = 100$ km/s, we find a flare energy of $E_{fl} = 2.2 \times 10^{35} \alpha^3 \beta^2$ erg which is a reasonable value for TRAPPIST 1 flares. A frequency of such flares is $f = 10^{-2}$ year$^{-1} = 1.2 \times 10^{-7}$ s$^{-1}$. The number of protons accelerated in one flare and the average rate of their generation as well as their density and flux within the first Parker spiral turn are presented in Tab. 2.

Maximum proton fluences and intensities for possible extreme events of stellar CR, Trappist-1d are presented in Tab. 3.
Table 2. The number of protons \( N \) accelerated in one flare and average rate of their generation, density and flux of protons within the first Parker spiral turn (1 AU)

| \( E_p \), MeV | \( N \), protons | \( fN \), proton/s | \( n = 3N/4\pi r_{park}^3 \), proton/cm\(^3\) | \( nV_{SW}/(2\pi) \), proton/(cm\(^2\) s sr) |
|---------------|-----------------|-----------------|-----------------|-----------------|
| 30            | \( 2.1 \times 10^{36} \) | \( 2.5 \times 10^{29} \) | \( 1.5 \times 10^{-4} \) | 1300            |
| 200           | \( 3.1 \times 10^{35} \) | \( 3.7 \times 10^{28} \) | \( 2.2 \times 10^{-5} \) | 191             |

Table 3. Maximum fluences and proton intensity for \( V_{SW} = 545 \) km/s in extreme events near TRAPPIST 1 d \((r_d = 0.0214 \) AU\)

| \( E_p \), MeV | \( N \), protons | \( F = 9N/\pi r^2 \), cm\(^{-2}\) | \( j_{max} = F/(2\pi\tau) \) (cm \( \cdot \) s \( \cdot \) sr\(^{-1}\)) |
|---------------|-----------------|-----------------|-----------------|
| 30            | \( 2.1 \times 10^{36} \) | \( 5.8 \times 10^{13} \) | \( 1.6 \times 10^{9} \) |
| 200           | \( 3.1 \times 10^{35} \) | \( 8.6 \times 10^{12} \) | \( 2.4 \times 10^{8} \) |

3.2. Estimates for \( \sigma \) Ori E

The magnetic helium-strong star \( \sigma \) Ori E is famous for its outstanding characteristics: the surface magnetic field strengths are at least 10 kG \([45]\), X-ray emission \( L_X/L_b = 10^{-7} \) \([46]\) and \( L_X/L_b = 3.9 \times 10^{-7} \), flare activity \([34, 39]\), a weak cold stellar wind of some \( 10^{-10}M_\odot \) year\(^{-1}\) \([48]\). Fundamental parameters of \( \sigma \) Ori E are \( T_{eff} = 22500 \) K, \( R = 3.77R_\odot \), \( M = 8.3M_\odot \), the rotation period \( P = 1.190847 \) days \([47]\). The estimated overall energy of X-ray from a flare observed at \( \sigma \) Ori E was between \( 5.3 \times 10^{35} \) and \( 2.9 \times 10^{36} \) \([34]\).

Applying the methods presented above we may get values of X-ray luminosity \( L_x \) and flare energy \( \alpha^3 \beta^2 E_{fl} \), which are very close to those observed. The mass rate of hot stellar wind appeared to be about 3-4 orders less than the observed mass rate of cold stellar wind \( 10^{-10}M_\odot \) year\(^{-1}\) \([48]\), that may explain why the hot stellar wind of \( \sigma \) Ori E is not observed. An electron density in the corona \( n_e \) was a free parameter in our calculations.

Table 4. Calculated parameters of the hot corona of \( \sigma \) Ori E

| \( T \), MK | \( n_e \), cm\(^{-3}\) | \( H_{cos}/R_* \) | \( L_X/L_b \) | \( M_r \) (\( M_\odot \), year\(^{-1}\)) | \( B_0 \), G | \( \alpha^3 \beta^2 E_{fl} \), erg |
|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 4.6            | \( 2.9 \times 10^{8} \) | 0.18            | \( 1.4 \times 10^{-7} \) | \( 4.0 \times 10^{-14} \) | 980            | \( 4.9 \times 10^{38} \) |
| 8.9            | \( 2.6 \times 10^{8} \) | 0.37            | \( 1.3 \times 10^{-7} \) | \( 1.7 \times 10^{-13} \) | 980            | \( 6.9 \times 10^{38} \) |

Table 5. Stellar wind parameters for \( \sigma \) Ori E in the habitable zone \((\sim 14 \) AU\)

| \( T \), MK | \( Q \), erg/s | \( n_{SW} \), cm\(^{-3}\) | \( u_{cr} \), km/s | \( r_{cr}/R_* \) | \( V_{SW} \), km/s | \( r_{park} \), AU | \( R_{AS} \) AU |
|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 4.6            | \( 1.2 \times 10^{30} \) | 0.5             | 218             | 2.6             | 1609            | 1.1             | 4051            |
| 8.9            | \( 1.2 \times 10^{31} \) | 1.6             | 392             | 1.4             | 2497            | 1.7             | 10770           |
Figure 2. The dependence of CR modulation in the habitable zone of σ Ori E for hypothetical values of magnetic field of 100 G–10 kG and coronal temperatures of 4.6 MK.

Figure 2 illustrates a possible effect of GCR modulation for hypothetical values of σ Ori E magnetic field of 100 G–10 kG and coronal temperatures of 4.6 MK. This value of coronal temperature is about twice as smaller as the maximum possible temperature for σ Ori E corona. Since the radius of the habitable zone is \( R_H \approx 14 \text{ AU} \gg r_{park} \sim 1 \text{ AU} \), we assumed a dimension of modulation region is about 30 AU. From Fig. 2 it is clear, that CR with energies less 1 TeV should be swept out from the astrosphere in a case of magnetic field \( > 5 \text{ kG} \). Moreover as \( R_{AS} \gg 30 \text{ AU} \) the real modulation GCR will be greater. However it is possible, that real values of the stellar magnetic field will be much less than measured. Flare observations may help to estimate their real values.

Assuming the following parameters of our active region: \( L = H_{\text{cor}} = \alpha R = 0.18R(0.37R) \), \( B = \beta B_0 = 980\beta  \text{ G} \), \( V = 100 \text{ km/s} \), we find a flare energy of \( E_f \alpha^3\beta^2 = 2.8 \times 10^{36} \beta^2 \text{ erg} \), which is very close to the observed flare energy \( 5.3 \times 10^{35} \text{–} 2.9 \times 10^{36} \text{ erg} \) [34], i.e., \( \beta = 0.44 \text{–} 0.29 \). The number of protons accelerated in such a flare as well as their density and flux within the radius of habitable zone are presented in Tab. 6. These values are in agreement with our previous estimates and conclusions [23].

Table 6. Number of protons, their maximum fluencies and intensities in habitable zone of σ Ori E (\( R_H = 14 \text{ AU} \), flare energy \( 2 \times 10^{36} \text{ erg} \))

| \( E_p \), MeV | \( N \), protons | \( F = 9N/(\pi r^2) \), cm\(^{-2} \) | \( j_{\text{max}} = F/(2\pi\tau) \), cm \cdot s \cdot sr\(^{-1} \) |
|---|---|---|---|
| 30 | \( 4.2 \times 10^{40} \) | \( 2.7 \times 10^{12} \) | \( 3.2 \times 10^{5} \) |
| 200 | \( 6.2 \times 10^{39} \) | \( 4.1 \times 10^{11} \) | \( 4.9 \times 10^{4} \) |

It is possible that the observed magnetic field at σ Ori E \( B_* = 10 \text{ kG} \) might be not the average stellar magnetic field but the local one (magnetic field of active region). In this case we may right \( \beta_* B_* = \beta B_0 \) and \( \beta_* = \beta B_0/B_* = 0.04 \text{–} 0.03 \). An average magnetic field should be much less than 10 kG, about several tens of Gauss, that is below the observational threshold.
4. Conclusions
It may be said that recent measurements by the Voyager I spacecraft gave birth to qualitative low energy CR astrophysics and have provided data of lower-energy cosmic-ray particles out of the heliosphere [49]. This gives us a reference point to evaluate low-energy CR intensities obtained by other methods in molecular clouds, protoplanetary discs and astrospheres. Our knowledge of the low CR interaction environment is at the same level as our knowledge of the heliosphere in the 1950s. So for the initial estimates we can use the Sun-stellar similarities and the methods developed for CR interaction with heliospheric medium. The most unknown parameter in these estimates is the stellar magnetic field which can vary by several orders of magnitude in comparison with solar magnetic field. The main problem is the measured stellar field may be the magnetic field of active regions, i.e., the local one. We believe that the developed approach can be used for any magnetic star with hot corona. Results for any planetary system should coincide with those obtained by more advanced models by the order of magnitude.

The estimates for stellar wind parameters, GCR and SCR parameters were found for the TRAPPIST 1 system. We obtain that for a coronal temperature of 2 MK the scale of astrosphere is $\sim 224$ AU and radius of the first Parker spiral is $\sim 1$ AU. Particles should be swept out by the stellar wind and the main factor of GCR modulation is the stellar wind magnetic field. As a result of modulation GCR less than 1 TeV should be absent near the planet. However, flare frequencies and energies allow us to state that the radiation environment determined by SCR.

For $\sigma$ Ori E applying the methods presented above we obtain the values of X-ray luminosity $L_X$ and flare energy $\alpha^3\beta^2E_{fl}$, which are very close to that observed. The mass rate of hot stellar wind appeared to be about 3–4 orders less than the observed mass rate of cold stellar wind $10^{-10}M_\odot$ year$^{-1}$ [48], which may explain why the hot stellar wind of $\sigma$ Ori E is not observed. From the flare energy estimations it is possible that the observed magnetic field at $\sigma$ Ori E might not be the average stellar magnetic field but the local one.

e-ASTROGAM is a concept of a breakthrough observatory carrying a $\gamma$-ray telescope for the study of the non-thermal Universe in the photon energy range from 0.15 MeV to 3 GeV. The gamma-rays of such energy give us a new source for understanding of low-energy CR.

The gamma-rays of energies from 0.15 MeV to 3 GeV may give us information for better understanding low-energy CR in their different locations in the Galaxy. e-ASTROGAM is a concept of a breakthrough observatory carrying a $\gamma$-ray telescope for the study of the non-thermal Universe in this new photon energy range [50, 51].

Acknowledgments
The work is supported by Russian Foundation for Basic Research grant 16-02-00328.

References
[1] Ginzburg V L 1988 Sov. Phys. Usp. 31 491
[2] Cummings A C, Stone E C, Heikkila B C, Lal N, Webber W R, Jóhannesson G, Moskalenko I. V, Orlando E, and Porter T A 2016 Astrophys. J. 831 18
[3] Neufeld D A, Wolfire M G 2017 Astrophys. J. 845 163
[4] Yang R-z, de Oa Wilhelmi E, and Aharonian F 2014 A&A 566 A142
[5] Phan V H M, Morlino G, Gabici S 2018 Monthly Notices Roy. Astronom. Soc. 480 5167
[6] Padovani M, Marcowith A, Hennebelle P, and Ferrière K 2016 A&A 590 A8
[7] Cleeves L I, Adams F C, and Bergin E A 2013 Astrophys. J. 772 5
[8] Rab Ch, G udel M, Padovani M, Kamp I, Thi W.-F, Woitke P, and Aresu G 2011 A&A 603 A96
[9] Fraschetti F, Drake J J, Cohen O, Garraffo C 2018 Astrophys. J. 853 112
[10] Padovani M, Icleve A V, Galli D, and Caselli F 2018 A&A 614 A111
[11] Grießmeier J-M, Stadelmann A, Motschmann U, Belisheva N K, Lammer H, Biernat H K 2005 Astrobiology 5 587
[12] Atri D, Harishan B, Grießmeier J-M 2013 Astrobiology 13 910
[13] Grießmeier J-M, Tabataba-Vakili F, Stadelmann A, Grenfell J L, Atri D 2015 Astrophys. J. 581 A44
[14] Grießmeier J-M, Tabataba-Vakili F, Stadelmann A, Grenfell J L, Atri D 2016 *Astrophys. J.* 587 A159
[15] Scherer K, Fichtner H, Stawicki O 2002 *J. Atmospheric Solar-Terrestrial Phys.* 64 795
[16] Cohen O, Drake J J, Kóta J 2012 *Astrophys. J.* 760 85
[17] Unsöld A 1957 *Proc. 4th IAU Symp.* p 238
[18] Edwards P J and McQueen M 1971 *Proc. 12th ICRC* 1 323
[19] Lovell A C B 1974 *Phil. Trans. Roy. Soc. A* 277 489
[20] Mullan D J 1979 *Astrophys. J.* 234 588
[21] Kopysov Yu S and Stozhkov Yu I 2005 *Proc. 29th ICRC* 3, 141
[22] Stozhkov Yu I 2011 *Bulletin of the Russian Academy of Sciences. Physics* 75 323
[23] Struminsky A. and Sadovski A 2017 *Stellar Cosmic Rays in a Habitable Zone, Stars: From Collapse to Collapse, Proc. conf. Special Astrophysical Observatory, Nizhny Arkhyz, Russia 3–7 October 2016* Ed Yu Yu Balega, D O Kudryavtsev, I I Roma-nyuk, and I A Yakunin (San Francisco: Astronomical Society of the Pacific) p 105
[24] Tabataba-Vakili F, Grenfell J L, Grießmeier J-M, Rauer H 2016 *A&A* 585 A96
[25] Atri D 2017 *MNRAS* 465 L34
[26] Sadovski A M, Struminsky A B, and Belov A 2018 *Astron Lett* 44 324
[27] Struminsky A B, Sadovski A M, and Zharikova M S 2018 *Geomagnetism Aeronomie* in print
[28] Parker E N *Astrophys. J.* 128 664
[29] Parker E N 1958 *Phys. Rev.* 110 1445
[30] Balona L A 2015 *MNRAS* 447 2714
[31] Berdyugina S V 2009 *Proceedings IAU Symp.* 259 323
[32] Linsky J L and Schöller M 2015 *Space Science Reviews* 191 26
[33] Güdel M 2004 *A&A Rev* 12 71
[34] Groote D and Schmitt J H M M 2004 *A&A* 418 235
[35] Balona L A 2012 *MNRAS* 423 3420
[36] Balona L A 2017 *MNRAS* 467 1830
[37] Hubrig S, Schöller M, Fossati L, Morel T, Castro N, Oskinova L M, Przybilla N, Eikenberry S S, Nieva M-F, Langer N 2015 *A&A* 578 L3
[38] Babel J and Montmerle T 1997 *A&A* 323 121
[39] Mullan D J 2009 *Astrophys. J.* 702 759
[40] Pedersen M G, Antoci V, Korhonen H, White T R, Jessen-Hansen J, Lehtinen J, Nikbakhsh S, Viuho J 2017 *MNRAS* 466 3060
[41] Gillon, M, Demory B.O, Van Grootel F, Motalebi F, Lovis C, Cameron A C, Charbonneau D, Latham D, Molinary E, Pepe F A, Segransan D, Sasselov D, Udry S, Mayor M, Micela G, Piotto G, and Sozzetti A 2017 *Nature* 542 456
[42] Vida K, Kovári Zs, Pál A, Oláh K, Kriskovics L 2017 *Astrophys. J.* 841 124
[43] Wheatley P J, Louden T, Bourrie V, Ehrenreich D, and Gillo M 2017 *MNRAS* 465L 74W
[44] Reiners A and Basri G A 2010 *Astrophys. J.* 710 924
[45] Landstreet J D and Borra O F 1978 *Astrophys. J.* 224 L5
[46] Pallavicini R, Golub L, Rosner R, Valiana G S, Ayres T, Linsky J L 1981 *Astrophys. J.* 248 279
[47] Townsend R H D, Rivinunus Th, Rowe J F, Moffat A F J, Matthews J M, Bohleender D, Neiner C, Teltong J H, Guenther D B, Kallinger T, Kuschnig R, Rucinski S M, Sasselov D, and Weiss W W 2013 *Astrophys. J.* 769 33
[48] Groote D and Hunger K 1982 *A&A* 116 64
[49] Stone E C, Cummings A C, McDonald F B, Heikkila B C, Lal N, Webber W R 2013 *Science* 334 150
[50] *Science with e-ASTROGAM* arXiv:1711.01265v4 [astro-ph.HE]
[51] Orlando E 2018 *MNRAS* 475 2724