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Cosmic Rays near Proxima Centauri b

Alexei Struminsky,[1,2] Andrei Sadovski,[1,3] and Anatoly Belov[4]

[1] Space Research Institute, Moscow, Russia
[2] Moscow Institute of Physics and Technology, Dolgoprudny, Moscow Region, Russia
[3] National Research University Higher School of Economics, Moscow, Russia
[4] IZMIRAN, Troitsk, Moscow, Russia

Abstract

Cosmic rays are an important factor of space weather determining radiation conditions near the Earth and it seems to be essential to clarify radiation conditions near extrasolar planets too. Last year a terrestrial planet candidate was discovered in an orbit around Proxima Centauri. Here we present our estimates on parameters of stellar wind from the Parker model, possible fluxes and fluencies of galactic and stellar cosmic rays based on the available data of the Proxima Centauri activity and its magnetic field. We found that galactic cosmic rays will be practically absent near Proxima b up to energies of 1 TeV due to the modulation by the stellar wind. Stellar cosmic rays may be accelerated in Proxima Centauri events, which are able to permanently maintain density of stellar cosmic rays in the astrosphere comparable to low energy cosmic ray density in the heliosphere. Maximal proton intensities in extreme Proxima events should be by 3–4 orders more than in solar events.

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1 Introduction

Kepler discoveries of new extrasolar planets give great impetus for discussions of life conditions and possible conditions for habitable zone (see for ex. Anglada-Escude et al., 2016; Garraffo et al., 2016; Grießmeier et al., 2015, 2016 and references within). Cosmic rays as a factor of space weather were considered only by one group, possibly, their first and most cited work in this regard is Grießmeier et al. (2005).

The dependence of the Galactic cosmic rays (GCR) induced radiation dose on the strength of the planetary magnetic field and its atmospheric depth were considered in different papers (Atri et al., 2013; Grießmeier et al., 2015). Grießmeier et al. (2016) studied atmospheric implications of cosmic rays near extrasolar Earth-like planets. The authors of the cited works supposed that for such planets the GCR rays flux can be regarded as an isotropic and approximately constant, since at the Earth orbit only the flux of low energy particles is slightly modulated by the solar activity. Low modulation of GCR means also a weak dependence of GCR flux on the orbital distance. However since stellar wind velocity and magnetic field as well as an activity of other stars (especially dwarfs as in the case of Proxima b) might be considerably higher in comparison with solar values, the modulation of GCR might be much stronger. Vidotto et al. (2014) mentioned the GCR modulation as a possible effect of the magnetized stellar wind, but without any estimate. Scherer et al. (2015) considered the modulation of GCR flux inside an astrosphere of λ Cephei. This is an O star and its cold stellar wind has another nature than the hot wind of active dwarfs. According to Schrere et al. (2015) the modulation in astrospheres of O-B stars affects particles up to 100 TeV. Modulation of GCR by astrospheres of dwarfs is not considered yet.

A similar problem of the GCR modulation near the archean Earth was considered by Scherer et al. (2002) and Cohen et al. (2012). Scherer et al. (2002) demonstrated by quantitative modeling 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 the increased cosmic ray fluxes. Cohen et al. (2012) showed that the GCR flux near the Archean Earth (for the early Sun) would has greatly reduced than is the case today mainly due to 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.

Since stellar cosmic rays are not detectable (or distinguishable) far away from their parent star they are step-sons of cosmic ray physics, generally they are mentioned as a possible component of CR ones per ten years (Unsold, 1957; Edwards & McQueen, 1971; Lovell, 1974; Mullan, 1979; Kopysov & Stozhkov, 2005; Stozhkov, 2011; Struminsky & Sadovski, 2017). Stellar cosmic rays (SCR) were considered in many papers (Tabataba-Vakili et al., 2016; Atri, 2017; Struminsky & Sadovski, 2017) as an important factor of space weather in a habitable zone of star. Since the details of SCR spectrum is unknown to model the effect of SCR one may use spectra of well known solar events (Atri, 2017) or average spectrum of solar proton events (Tabataba-Vakili et al., 2016). Another approach is to base on general physical principles (Struminsky & Sadovski, 2017) assuming solar-stellar analogies, which is not based on near Earth observations of solar cosmic rays.

The red dwarf Proxima Centauri (α Centauri C, GL 551, HIP 70890 or simply Proxima) is the Sun's closest (1.295 parsecs) stellar neighbor and one of the best-studied low-mass stars. It has an effective temperature of only around 3,050 K, a luminosity of $0.15L_\odot$ (the index $\odot$ determines the Sun parameters), a measured radius of $0.14R_\odot$ and a mass of about $0.12M_\odot$ (GJ 551; dM5.5e) (see Anglada-Escude et al. (2016)). Anglada-Escude et al. (2016) reported the presence of a small planet with a minimum mass of about 1.3 Earth masses orbiting Proxima with a period of approximately 11.2 days at a semi-major-axis distance of around 0.049 AU so it should rotate in the star's habitability zone.

Proxima is considered as a moderately active star and its quiescent activity levels and X-ray luminosity are comparable to those of the Sun. Wargelin et al. (2017) summarized several years of optical, UV, and X-ray observations of Proxima Centauri. They confirmed previous reports of an 83-day rotational period and find strong evidence for a 7-year stellar cycle, along with indications of differential rotation at about the solar level. The very long rotation period of Proxima Centauri renders rotation-based Doppler shifts well below the resolution limit, and surface magnetic field maps are not currently available (Garraffo et al., 2016). There is only a single measurement of the average magnetic field strength on Proxima (Reiners & Basri, 2008), which showed moderate magnetic flux of $450\ \mathrm{G} < B_f < 750\ \mathrm{G}$ (3σ). The X-ray/UV intensity of the Proxima's emission anti-correlates with optical V-band brightness for both rotational and cyclical variations, possibly, and shows that all these variations are driven by magnetic activity. Optical intensities anti-correlates with the higher energy emission showing a minimum of magnetic activity (and minimum X-ray/UV emission) when the star is optically brightest (least spotty), unlike the relatively inactive Sun. The cycle amplitude of Prox Cen in X-rays is relatively small, with maximum and minimum X-ray luminosities $L_{\max\mathrm{X}}/L_{\min\mathrm{X}}$ roughly 1.5 versus 2–6 for the G and K stars (Güdel et al., 2004).

The flare activity of Proxima Centauri is well known and was reported in a number of papers (Thackeray, 1950; Walker, 1981; Haisch et al., 1983, 1995; Güdel et al., 2004; Davenport et al., 2016). According to recent MOST observations of flares on Proxima Centauri (Davenport et al., 2016) flares with flux amplitudes of 0.5% occur 63 times per day, while super flares with energies of 10^{33} erg occur 8 times per year. Comparing to other M5–M6 stars suggests Proxima was more active in its youth. A quiescent luminosity for Proxima Cen in the MOST bandpass is of $\log L_0 = 28.69$ erg s^{-1}.

Garraffo et al. (2016) constructed 3-D MHD models of the wind and magnetic field around Proxima Centauri using a surface magnetic field map for a star of the same spectral type and scaled to match the observed 600 G surface magnetic field strength. They probed two different scalings of the magnetic field: field amplitude is equal 600 G and the mean magnetic field is 600 G so the maximum value is 1200 G). The wind speeds obtained by their model are not drastically different to the solar wind ones and consist up to 1300 km s^{-1} for the lower magnetic field case and up to 1600 km s^{-1} for the higher magnetic field case. The wind densities at Proxima b's orbital distance are 100 to 1000 cm^{-3}.

The goal of this work is to estimate stellar wind properties, fluxes of galactic and stellar cosmic rays near Proxima Centauri b accounting for the stellar activity. We will use simple formulae with clear physical sense, which have been proposed in the beginning of space era. These formulae give answers with accuracy of factor 2–3 for the Sun and the Earth. Since the assumptions under which these formulae were derived do not dependent on the star, we suppose that our results for Proxima Centauri would have the same accuracy. The reason for using such approach is that we don't know more about Proxima Centauri than the people knew about the Sun in the fifties of the last century. Furthermore such simple modeling allows obtaining the full picture of the processes in extra–solar systems without knowing details of the processes on the star and in the star's wind. Moreover such quality estimations by the order of magnitude can help to find relevant values of parameters and compare them with solar values. Such evaluations should allow simplifying subsequent equations and numerical simulations.

In the Sec. 2 we perform some estimates on properties of stellar wind in the astrosphere of Proxima and compare them with the existing model. Section 3 is devoted to the galactic cosmic rays modulation and in Sec. 4 we make some derivation for the stellar cosmic rays. Sec. 5 is the conclusion.

2 Stellar wind and astrosphere of Proxima Centauri

According to Parker (1958) we may estimate a sound speed depending on the coronal electron temperature as $u_{cr} = \sqrt{2kT_e/m_p}$, a radius of the critical point as $r_{cr} = GM/u_{cr}^2$ and stellar wind velocity as $V_{SW} \approx u_{cr}\ln(r_b/r_{cr})$.

Knowing a velocity of stellar wind we may also estimate its density. The rate of thermal loss is

$$Q = -\frac{8\pi}{7}R_* k(T_{c*})T_{c*},$$

where R_* is the stellar radius, T_{c*} is the coronal temperature and $k(T_{c*}) = 6\times10^{-6}T_{c*}^{5/2}$ erg cm^{-1} s^{-1} K^{-1} is the coefficient of heat conductivity for a fully ionized gas. If all of the heat flux Q went into an expanding spherical corona

$$Q \approx 4\pi r^2 m_p \frac{NV}{2}(V_{SW}^2 + V_{esc}^2),$$

where N is the coronal density at distance r, m_p is the proton mass, V_{SW} is the constant stellar wind speed and $V_{\mathrm{esc}} = \sqrt{2GM_*/R_*} = 568$ km s^{-1} is the escape velocity for Proxima Centauri.

This approach is summarized in Lang (1980) and provides reasonable values for the Sun with accuracy of about one order of magnitude for the coronal temperature 10^6 K.

According to the X-ray observations the coronal temperature of Proxima is 2.7×10^6 K (Johnstone & Güdel, 2015). Note that if $T_e \geq 4.6\times10^6$ K a critical point would be below the surface of Proxima, i. e. this is the maximal temperature for a quiet corona.

Knowing properties of the stellar wind we may estimate the radius of the Proxima astrosphere, that is $R_{\mathrm{AS}} = R_b(m_p n V^2/P_{\mathrm{ISM}})^{1/2}$, where $P_{\mathrm{ISM}} = 0.17$ eV cm^{-3} is the energy density of local interstellar medium. The results of calculations of stellar wind parameters for two coronal temperatures are shown in Tab. 1. Even for the maximal possible coronal temperature of 4.6×10^6 K the stellar wind speed is 1200 km/s that is well below the wind speeds obtained by Garraffo et al. (2016). It is not clear from the model of Garraffo et al. (2016), how is it possible to change the position of the critical point accounting the coronal magnetic field?

For the solar wind we have a natural parameter to normalize any solar system values—the solar radii. If we normalize the distance from Proxima to Proxima b via the star radii we obtain that $R_{Pb} = 0.049\ \mathrm{AU} = 7.35\times10^{11}\ \mathrm{km} = 72R_P$, so it is more reasonable to compare the conditions near Proxima b with ones near the Mercury orbiting at 64 solar radii.

Table 1: Parameters of stellar wind.

T, MK	Q, erg	H/R_*, 10^{-1}	$U_{\rm cr}$, 10^2 km s^{-1}	$R_{\rm cr}/R_*$	V, 10^2 km s^{-1}	N, 10^3 cm^{-3}	$R_{\rm AS}$ 10^2 AU
2.7	7.026×10^{27}	2.880	2.158	1.736	8.065	1.977	4.261
4.6	$\mathbf{4.535 \times 10^{28}}$	**4.907**	**2.817**	**1.019**	**1.203**	**4.320**	**9.394**

3 Proxima Centauri modulation of galactic cosmic rays

According to Parker (1958) the GCR modulation by solar wind occurs inside the solar wind shell, which extends uniformly and with spherical symmetry, from a solar distance $r = r_1$ out to $r = r_2$. Assumed that solar wind has magnetic field B and velocity V_{SW}, $l = 2 \times 10^{11}$ cm. The steady state cosmic ray density $j_0(\eta)$ inside the modulation shell is related to the galactic density $j_\infty(\eta)$ outside by

$$j_0(\eta) = j_\infty(\eta) \exp\left\{ -\frac{12 V_{SW} \, (r_1 - r_2) \, l Z^2 e^2 B^2 (\eta + 1)}{\pi^2 m^2 c^5 \, [\eta(\eta+2)]^{3/2}} \right\},$$

where a particles have mass m, charge Ze, and kinetic energy ηmc^2.

Reasonable values of $j_0(\eta)/j_\infty(\eta)$ (GCR modulation) near the Earth were obtained by Parker (1958) assuming $B \approx 2 \times 10^{-5}$ G, $r_1 - r_2 = 4$ AU, $v = 1000$ km/s.

In a case of Proxima b $B \approx (1–2) \times 10^{-1}$ G, $v = 800$–1200 km/s. A radius of the Parker spiral for Proxima is 23–43 AU, within this range B would not be constant, so for estimates we will take $r_1 - r_2 = 5$ AU. Results of calculations are presented in Fig. 1. We see that GCR protons with energies less than 1 TeV do not reach Proxima b, they are swept out by the stellar wind, the diffusion is not effective. It is clear that larger values of stellar wind velocity Garraffo et al. (2016) and shell should lead to stronger effects of GCR modulation.

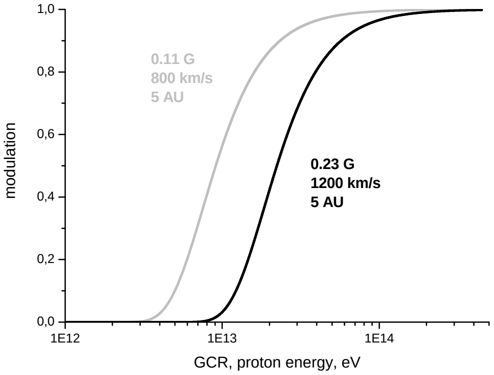

Figure 1: Calculated modulation $j_0(\eta)/j_\infty(\eta)$ for GCR near Proxima b.

4 Stellar cosmic rays

The equipartition magnetic field strength is the minimum possible value for the field strength dynamic flare loops. Equating average magnetic field stellar surfaces to the field strength at which the magnetic field balances the thermal pressure of surrounding gas, $B^2/8\pi = nkT = Gm_p M_P H/R^2$, and in assumption that characteristic scale is equal to the mean free path $H = (n\sigma_T)^{-1}$ (σ_T is the Thompson cross-section), we obtain the estimation of the photospheric magnetic field strength

$$B_0 = \frac{1}{R} \left(\frac{8\pi G m M}{\sigma_T} \right)^{1/2}.$$

Maximal energy of Proxima protons accelerated in active region. Parameters of the typical active region are $L = \alpha R = \alpha 0.145 \times 0.7 \times 10^{10}$ cm $= \alpha 10^{10}$ cm, $\alpha \lesssim 1$; $B = \beta B_0 \sim 3150\beta$ G; $V = 100$ km/c, and

$$E = \frac{1}{c} VB = \beta \times 1 \text{ CGSE},$$

$$U_{\max} = \alpha e E R = 3150 \alpha\beta \text{ GeV}.$$

Maximal energy of Proxima CR is less than a minimal non-modulated energy of galactic CR. Spectra of stellar and galactic cosmic rays are not overlapped close to Proxima b.

Flare energy we may express (Balona, 2015; Struminsky & Sadovski, 2017) as $E_{fl} \alpha^3 \beta^2 = 4.0 \times 10^{35} \alpha^3 \beta^2$ erg. Therefore 10^{33} erg is a quite reasonable value of flare energy, according to the MOST observation (Davenport et al., 2016) eight such flares per year occur, so their frequency is $f = 3.2 \times 10^{-8}$ s^{-1}. Let 10% of the flare energy were released into proton acceleration, then we may perform the Table 2.

Table 2: Full number of protons in flare

Energy, MeV	N, protons	fN, protons/s
30	2×10^{36}	6.4×10^{28}
200	3×10^{35}	9.9×10^{27}

Densities and fluxes of stellar cosmic rays in the modulation region (the first turn of the Parker spiral) are presented in Table 3.

The main transport process of SCR is the convection. A characteristic time is $\tau = r/V = 4.2$ hours for $V = 484$ km/s (or 2.3 h for $V = 900$ km/s).

If all accelerated protons will propagate within spatial angle 60×60 degrees, then fluence would be $F = 9N/\pi r^2$ and the maximal intensity as $j_{\max} = F/(2\pi\tau)$ (Tab. 4. Two different values of $j_{\max}$ in Table 4 correspond to different values of characteristic time.

A 1/6 of the Proxima b year is 44 hours, i. e. dynamics of SCR intensity would be determined by radial propagation of the stellar wind. The obtained fluencies are 2–3 orders more

Table 3: Densities and fluxes of stellar cosmic rays in the modulation region.

Energy, MeV	n, cm^{-3}		$nV/(2\pi)$, (cm^2 s st)$^{-1}$	
	$V_{SW} = 484$ km/s, 23 AU	$V = 900$ km/s, 43 AU	$V_{SW} = 484$ km/s, 23 AU	$V = 900$ km/s, 43 AU
30	1.2×10^{-8}	1.8×10^{-9}	0.099	0.025
200	1.7×10^{-9}	2.7×10^{-10}	0.013	0.0038

Table 4: Proton fluence for Proxima b.

Energy, MeV	N, protons	F, cm^{-2}	$j_{\max}$, (cm^2 s st)$^{-1}$	j, (cm^2 s st)$^{-1}$
30	2×10^{36}	1.1×10^{13}	1.2×10^8–3.0×10^8	$1.6 \times 10^{11}\beta^2$
200	3×10^{35}	1.6×10^{12}	1.6×10^7–4.4×10^7	$5.7 \times 10^{10}\beta^{\mathbf{2}}$

than the 30 MeV proton fluence of 8×10^{10} cm^{-2} estimated for the 775AD solar proton event.

The obtained values of $j_{\max}$ we may compare with estimates according to formulae of Freier & Webber (1963), which would be $j = \beta^2 B_0^2 R^4 v/(32\pi^2 r^4 E_p)$ in our case, here v is the proton velocity. We may get a coincidence between j and $j_{\max}$ for reasonable values of β.

5 Conclusions

Cosmic rays are an important factor of space weather determining radiation conditions near planets so it is essential to know radiation conditions near extrasolar planets.

We made estimates on parameters of stellar wind on the basis of the Parker model, possible fluxes and fluencies of galactic and stellar cosmic rays based on available data of the Proxima Centauri activity and its magnetic field.

The simple models, which were derived for the Sun in 1950^{th}–1960^{th}, give the reasonable results for the star wind parameters and conditions on the orbit of Proxima b. For the first time and from the first principals with the help of available data the estimation of the radiation conditions near Proxima b was made.

The obtained data showed that galactic cosmic rays will be absent near Proxima b up to energies till 1 TeV due to the modulation by the stellar wind. However stellar cosmic rays may be accelerated in stellar flares and swept out from the astrosphere by the wind. Flares at Proxima Centauri are able to maintain constant density of stellar cosmic rays in the astrosphere. Maximal proton intensities in extreme Proxima events should by 3–4 orders more than in solar events.

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