

Radiation conditions near exoplanets

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The goal

- is to estimate fluxes of galactic and stellar CR near exoplanets accounting the stellar activity using simple models elaborated in the beginning of space era for the solar wind (Parker, 1958), GCR modulation (Parker, 1958), stellar CR (Hayakava,1969).
- Here we will apply these methods to Trappist 1 d-f

Galactic Cosmic Rays (GCR) near exoplanets

- Griebmeier et al.(2015) considered the dependence of the Galactic cosmic rays (GCR) induced radiation dose on the strength of the planetary magnetic field and its atmospheric depth. **GCR modulation was not considered!**
- GCR modulation was considered near the Archean Earth 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 have been greatly reduced than is the case today, is 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.
- Struminsky et al. (2017) considered radiation conditions close to Proxima b. They should be determined by stellar CR since there are no GCR due to GCR modulation by the stellar wind.

Stellar Wind (Solar wind, Parker, 1958)

$$1. U_{cr} = \left(\frac{2k_B T_{c*}}{m_p} \right)^{1/2}$$

$$2. r_{cr} = \frac{GM_*}{2U_{cr}^2}$$

$$3. V_{SW} \approx U_{cr} \ln \left(\frac{r}{r_{cr}} \right)$$

$$4. r_1 = VT \frac{\varphi}{2\pi}$$

$$5. B(r) = B_{ph} \left(\frac{R_*}{r} \right)^2$$

$$1. Q = -\frac{8\pi}{7} R_* k(T_{c*}) \cdot T_{c*}$$

$$2. V_{esc} = \sqrt{\frac{2GM_*}{R_*}}$$

$$3. Q \approx 4\pi r^2 m_p \frac{NV}{2} (V^2 + V_{esc}^2)$$

$$4. N(r) \quad V(r)$$

$$R_{SS} = R_b \sqrt{\frac{m_p n V^2}{P_{ISM}}}$$

The maximal possible coronal temperature corresponds to the critical point below the stellar surface.

Cosmic-Ray Modulation by Solar Wind*

E. N. PARKER

Enrico Fermi Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois

(Received February 19, 1958)

Elementary kinetic theory tells us that the coefficient of diffusion of particles with a velocity w and mean free path L is

$$\begin{aligned} \kappa(\eta) &\cong \frac{1}{3} w(\eta) L(\eta) \text{ cm}^2/\text{sec} \\ &= \frac{\pi^2}{12} \left(\frac{M^2 c^5}{Z^2 e^2 B^2 l} \right) \frac{[\eta(\eta+2)]^{\frac{3}{2}}}{(\eta+1)}. \end{aligned} \quad (3)$$

If the diffusing medium (the magnetic irregularities) has a general motion \mathbf{v} , the diffusive and convective transport equation is⁷

$$\partial j(\eta)/\partial t = -\nabla \cdot [\mathbf{v} j(\eta)] + \nabla \cdot [\kappa(\eta) \nabla j(\eta)] \quad (4)$$

for the density $j(\eta)$ of cosmic-ray particles with energy η .

Supposing that the disordered shell extends uniformly, and with spherical symmetry, from a solar distance $r=r_1$ out to $r=r_2$, we have upon integration of (4) that the steady-state cosmic-ray density $j_0(\eta)$ inside the shell is related to the galactic density $j_\infty(\eta)$ outside by

$$j_0(\eta) = j_\infty(\eta) \exp \left\{ -\frac{12v(r_2-r_1)lZ^2e^2B^2(\eta+1)}{\pi^2 M^2 c^5 [\eta(\eta+2)]^{\frac{3}{2}}} \right\}. \quad (5)$$

If we suppose that we have the typical values mentioned above, $l \cong 2 \times 10^6$, $B \cong 2 \times 10^{-5}$ gauss, $r_2 - r_1 = 4$ astronomical units (6×10^{13} cm), and $v = 10^3$ km/sec, then we have

$$j_0(\eta) = j_\infty(\eta) \exp \{ -2.16(\eta+1)/[\eta(\eta+2)]^{\frac{3}{2}} \} \quad (6)$$

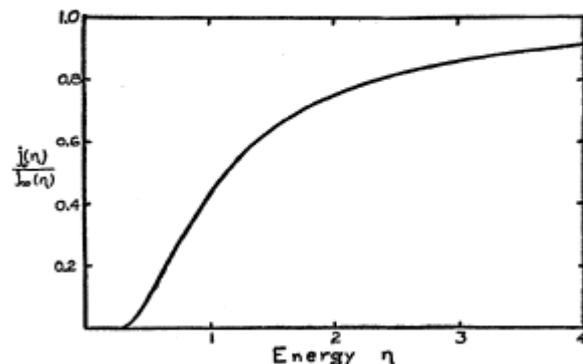


FIG. 1. Heliocentric depression of the cosmic-ray intensity in the inner solar system by the solar wind in the heliocentric shell of disordered magnetic field.

Stellar Cosmic Rays (SCR) near exoplanets

- Tabataba-Vakili et al. (2015) considered an influence of stellar cosmic rays (SCR) on atmospheres of exoplanets assuming stellar CR spectrum as solar at 1 AU (Kuznetsov et al., 2005) scaled as a square of radial distance.
- Atri (2016) considered an influence of SCR, using spectra of well known solar events - hard 23.02.1956 (SPE56), soft - 4.08.1972 (SPE72), medium -29.09.1989 (SPE89).
- **Effects of SCR propagations were not considered!**
- Struminsky et al. (2017) estimated fluxes of SCR near Proxima b from general physical principles.

Stellar CR, general ideas

$$E_{CR} = 10\% E_{flare}$$

$$L = \alpha R_*$$

$$E_{flare} = \frac{B_{cor}^2}{8\pi} L^3$$

$$B_{cor} = \beta B_{eq}$$

V – Characteristic
plasma velocity

$$N_p = \frac{E_{CR}}{E_p}$$

$$E_{max} = \frac{\alpha\beta}{c} V B_{eq} R_*$$

$$n_p = \frac{N_p}{V_1}$$

fN_p – proton production per second,
 f – frequency of flares

Estimate of equipartition magnetic field

$$\frac{B^2}{8\pi} = nkT$$

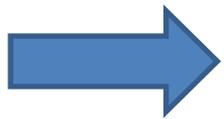
$$H = \lambda = \frac{1}{4\pi\sigma_T}$$

$$\rho G \frac{M}{R^2} H = nkT$$



$$B_{\text{PH}} = \frac{1}{R} \sqrt{\frac{8\pi GmM}{\sigma_T}}$$

$$B_{\text{OC}} = \frac{1}{R_c} \sqrt{\frac{8\pi GmM_c}{\sigma_T}} = 1283 \text{Gs}$$



$$B = B_{\text{OC}} \frac{R_c}{R} \sqrt{\frac{M}{M_c}}$$

Seven planets of Trappist 1

- 2MASS J23062928-0502285 - TRAPPIST (TRAnsiting Planets and Planetesimals Small Telescope) ESO.
- [Gillon et al., 2017, Nature, Volume 542, Issue 7642, pp. 456-460](#)
- “...Recently, three Earth-sized planets were detected that transit (that is, pass in front of) a star with a mass just eight per cent that of the Sun, located 12 parsecs away. The transiting configuration of these planets, combined with the Jupiter-like size of their host star—named TRAPPIST-1—makes possible in-depth studies of their atmospheric properties with present-day and future astronomical facilities. Here we report the results of a photometric monitoring campaign of that star from the ground and space. Our observations reveal that at least seven planets with sizes and masses similar to those of Earth revolve around TRAPPIST-1...”

Trappist 1

- [Red dwarf](#) M8 V.
- The stellar radius is 12,1 % of the solar one, that is a little larger than the Jupiter radius.
- The stellar mass is $0,080 \pm 0,007$ of the solar mass, i.e. ~ 84 masses of Jupiter.
- The surface temperature is 2559 ± 50 K.
- TRAPPIST-1 is a too weak source to get ZDI magnetic field maps by using modern instruments, the measured average magnetic field is 600 G (Reiners & Basri 2010).

Stellar activity and wind

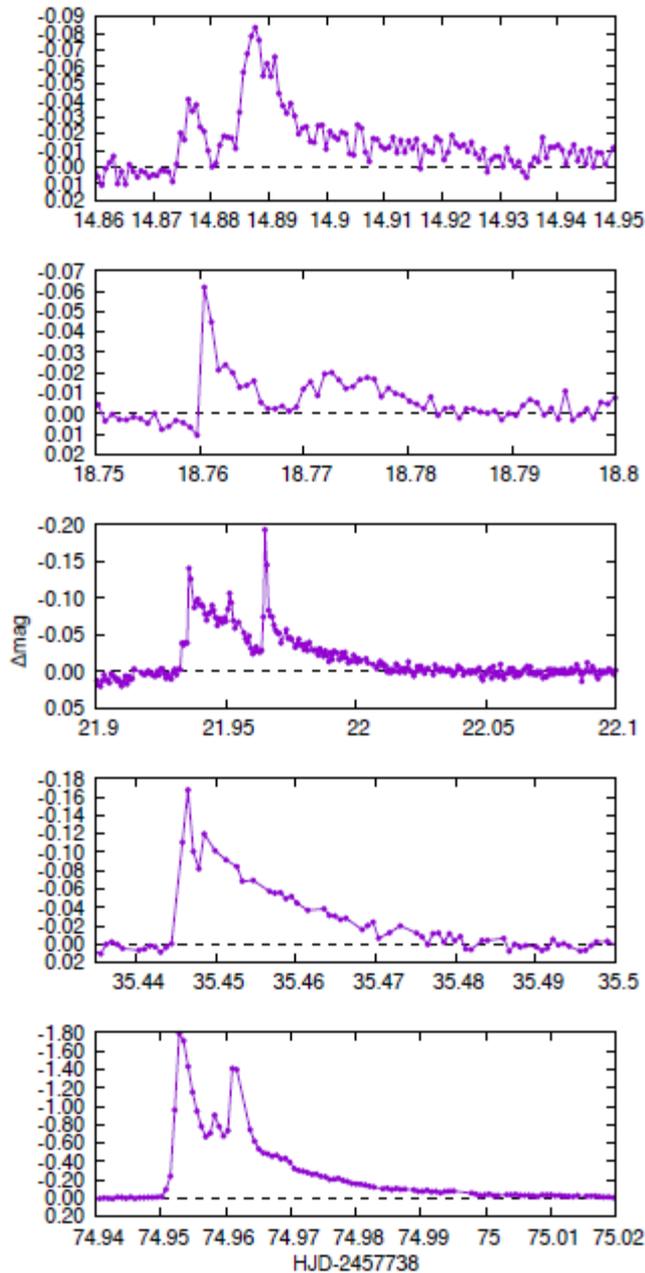


Figure 3. Light curves of the five complex flare events.

- **Vida et al., 2017** analyzed the K2 light curve of the TRAPPIST-1 system. The Fourier analysis of the data suggests $P_{rot} = 3:2950:003$ days. The light curve showed several flares, of which 42 events with integrated flare energies of $1.26 \cdot 10^{30}$ до $1.24 \cdot 10^{33}$ ergs. Approximately 12% of the flares were complex, multi-peaked eruptions.
- **Wheatley et al. 2017** - XMM Newton observations confirmed an existence of the hot corona $LX/L_{bol} = (2-4) \cdot 10^{-4}$.
- There should be a stellar wind similar to the solar wind.

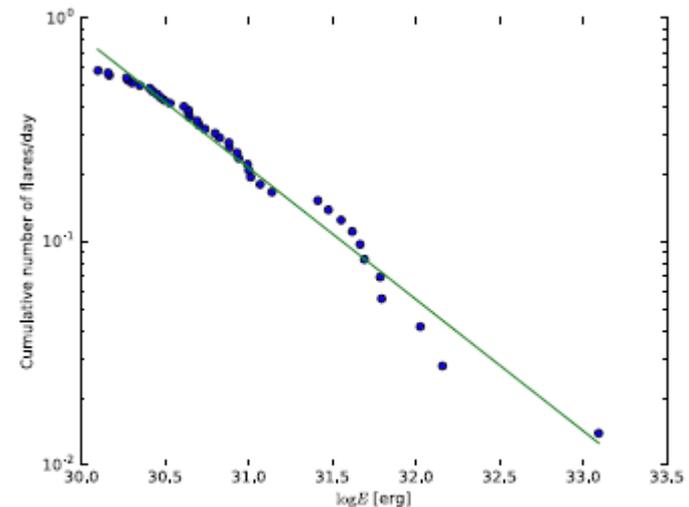


Figure 4. Cumulative flare frequency distribution fitted by a linear function

Magnetic and Plasma Environment of the TRAPPIST-1 Planets

- [Garraffo et al. 2017](#) used state-of-the-art 3D MHD models to simulate the wind around TRAPPIST-1 and study the conditions at each planetary orbit.
- All planets experience a stellar wind pressure between 10^3 and 10^5 times the solar wind pressure on Earth.
- All orbits pass through wind pressure changes of an order of magnitude and most planets spend a large fraction of their orbital period in the sub-Alfvénic regime.
- For plausible planetary magnetic field strengths, all magnetospheres are greatly compressed and undergo much more dynamic change than that of the Earth.
- These conditions could result in strong atmospheric stripping and evaporation and should be taken into account for any realistic assessment of the evolution and habitability of the TRAPPIST-1 planets

Stellar wind and astrosphere of Trappist 1

D, 0.02145 AU, slow wind

$$T_{c*} = 1.5 \cdot 10^6 \text{ K}$$

$$U_{cr} = 161 \text{ km/s}$$

$$r_{cr} = 2.6 \cdot R_{Tr}$$

$$V_{SW} = 442 \text{ km/s}$$

$$r_1 = VT \frac{\varphi}{2\pi} = 0.82 \text{ AU}$$

$$Q = -\frac{8\pi}{7} R_* k(T_{c*}) \cdot T_{c*} = -7.0 \cdot 10^{26} \text{ эрг/с}$$

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

$$n = 4652 \text{ cm}^{-3} \quad V = 442 \text{ km/s}$$

$$R_{SS} = R_b \sqrt[2]{\frac{m_p n V^2}{P_{ISM}}} = 157 \text{ AU} \quad P_{ISM} = 0.17 \text{ эВ}$$

F, 0.0371 AU, fast wind

$$T_{c*} = 3.8 \cdot 10^6 \text{ K}$$

$$U_{cr} = 256 \text{ km/s}$$

$$r_{cr} = 1 \cdot R_{Tr}$$

$$V_{SW} = 1082 \text{ km/s}$$

$$r_1 = VT \frac{\varphi}{2\pi} = 2 \text{ AU}$$

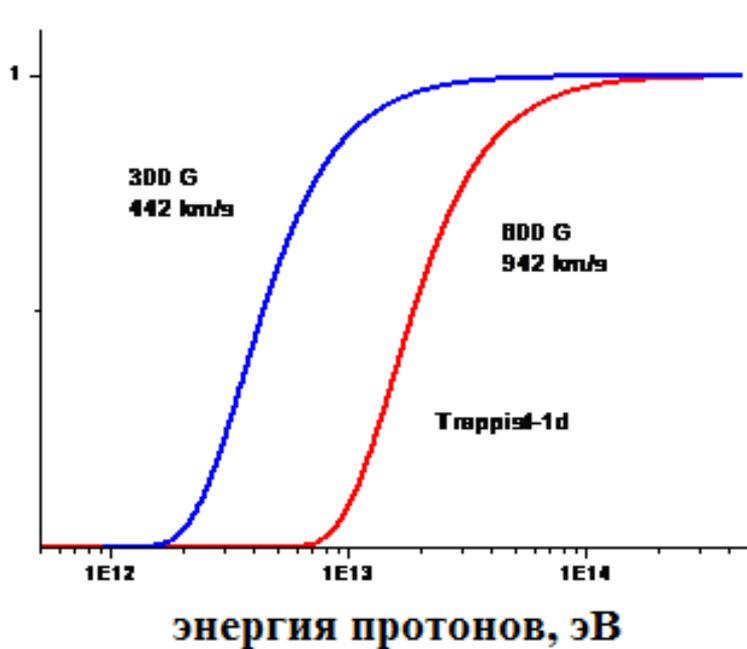
$$Q = -\frac{8\pi}{7} R_* k(T_{c*}) \cdot T_{c*} = -1.8 \cdot 10^{28} \text{ эрг/с}$$

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

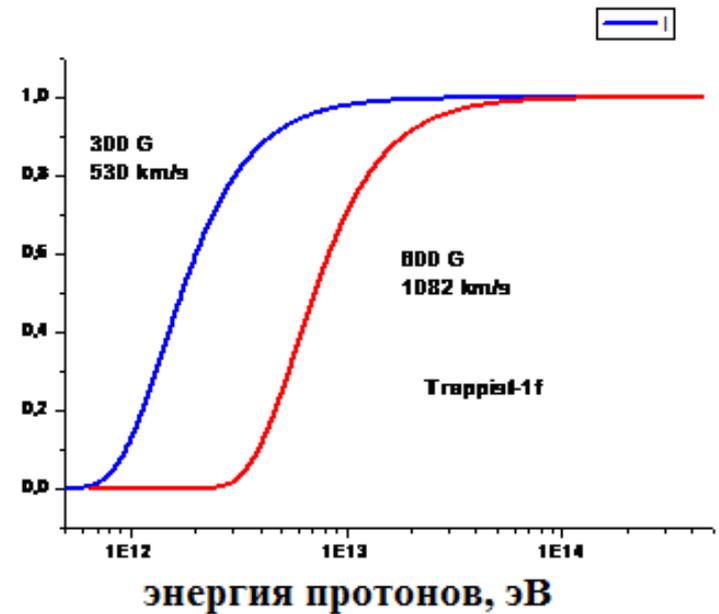
$$n = 4155 \text{ cm}^{-3} \quad V = 1082 \text{ km/s}$$

$$R_{SS} = R_b \sqrt[2]{\frac{m_p n V^2}{P_{ISM}}} = 627 \text{ AU} \quad P_{ISM} = 0.17 \text{ эВ}$$

GCR modulation near Trappist-1d-f



Proton energy, eV



Proton energy, eV

Stellar CR. Trappist 1

$$E = \frac{1}{c}VB = \beta \cdot 1 \cdot CGSE$$

$$U_{\max} = \alpha eER = \alpha\beta \cdot 2550 GeV$$

Parameters of active region $L = \alpha R = \alpha 8.5 \cdot 10^9$ cm;
 $B = \beta B_0 = 3000 \cdot \beta$ G; $V = 100$ km/s.

$E_{fl} \alpha^3 \beta^2 = 2.2E35 \alpha^3 \beta^2$ erg $10E33$ erg is a reasonable value, a frequency of such flares is $f = 1E-2$ 1/день = $1.2E-7$ 1/s

Let 10% of the flare energy goes into proton acceleration, then

	N, protons	fN, protons/s
30 MeV	2E36	2.4E29
200 MeV	3E35	3.8E28

Density and flux of protons within the first Parker spiral turn are

	n, protons/cm**3		nV, protons/cm**2/s/st	
	V=442 km/s	V=1082 km/s	V=442km/s	V=1082 km/s
30 MeV	3E-4	1.8E-5	2110	309
200 MeV	4E-5	2.7E-6	281	46

Extreme events of stellar CR, Trappist-1 d, f

D 0.02145 AU	N, protons	F, cm ⁻² 0.82 AU	(cm ² s st) ⁻¹
30 MeV	2E36	5.5E13	1.2E9
200 MeV	3E35	8.3E12	1.8E8

F 0.0371 AU	N, protons	F, cm ⁻² 2 AU	(cm ² s st) ⁻¹
30 MeV	2E36	1.9E13	5.8E8
200 MeV	3E35	2.8E12	8.8E7

- Particles should be swept out by the stellar wind!
- Characteristic time (SW propagation to the planet orbit) $T = 2$ hours for D and 442 km/s (1.4 hours for 1080 rv/s and F.)
- Proton propagation within 60*60 degrees, 1/6 of the stellar rotation period of 3.3 days would be 0.55 day = 13.2 hours
- Radial plasma propagation should determine dynamics of SCR.
- Fluences should be by 2-3 orders higher than in the largest Earth event of 775AD (8E10 cm⁻²)
- Maximal intensities $I_{max}=F/T$ should be 3-4 orders higher.

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 Trappist 1 activity and its magnetic field.
- The simple models, which were derived for the Sun in 1950th-1960th, give the reasonable results for the star wind parameters and conditions on the orbit of Trappist 1 D and F. For the first time and from the first principals with the help of available data the estimation of the radiation conditions in the habitable zone of Trappist 1 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 Trappist 1 are able to maintain constant density of stellar cosmic rays in the astrosphere. Maximal proton intensities in extreme Trappist 1 events should be by 3-4 orders more than in solar events.