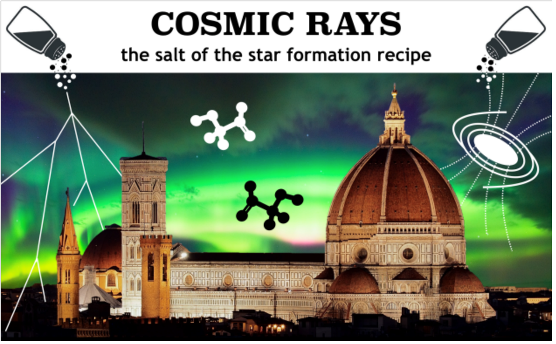

Radiation conditions near exoplanets of G-M stars

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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

- Grießmeier 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 has 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.
- Sadovski et al. (2017) considered radiation conditions close to Proxima b. It’s appeared that stellar CR should determine radiation conditions, since there are no GCR due to GCR modulation by the stellar wind.

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Cosmic-Ray Modulation by Solar Wind*

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

$$\kappa(\eta)\cong\tfrac{1}{3}w(\eta)L(\eta)\ \mathrm{cm}^2/\mathrm{sec}$$
$$=\frac{\pi^2}{12}\left(\frac{M^2c^5}{Z^2e^2B^2l}\right)\frac{[\eta(\eta+2)]^{\frac{3}{2}}}{(\eta+1)}. \tag{3}$$

If the diffusing medium (the magnetic irregularities) has a general motion $\mathbf{v}$, the diffusive and convective transport equation is[7]

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

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

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

If we suppose that we have the typical values mentioned above, $l\cong2\times10^6$, $B\cong2\times10^{-5}$ gauss, $r_2-r_1=4$ astronomical units (6×10^{13} cm), and $v=10^3$ km/sec, then we have

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

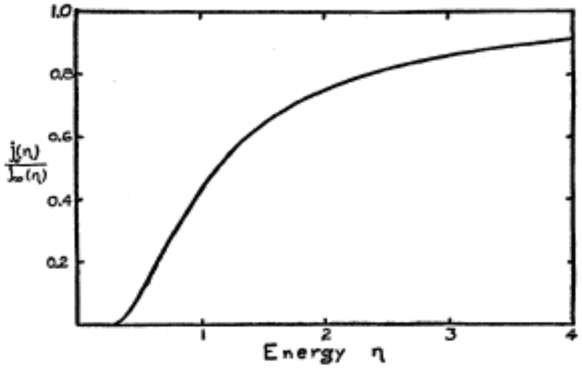


FIG. 1. Heliocentric depression of the cosmic-ray intensity in the inner solar system by the solar wind in the heliocentric shell of disordered magnetic field.

What we need to know?

- Stellar wind velocity (coronal temperature, over heating)
- Radius of the first Parker spiral turn (Stellar rotation period)
- Diffusion coefficient (interplanetary magnetic field, photospheric magnetic field of hosting star)

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. $V_{esc} = \sqrt[2]{\frac{2GM_*}{R_*}}$
3. $Q \approx 4\pi r^2 m_p \frac{NV}{2}(V^2 + V_{esc}^2)$
4. *N(r)   V(r)*

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

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

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

Balona, 2015

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

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

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

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

$$L = \alpha R_*$$

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

V – Characteristic plasma velocity

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

fNp – proton production per second,

f –frequency of flares

SCR propagation. What need we to know?

- distribution of flare energy
- Frequency of flares
- Diffusion coefficient (interplanetary magnetic field - stellar photospheric magnetic field)
- Stellar wind velocity

Estimate of equipartition magnetic field

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

$$H=\lambda=\frac{1}{n\sigma_T}$$

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

$$\Rightarrow \quad B_{ph}=\frac{1}{R}\sqrt{\frac{8\pi GmM}{\sigma_T}}$$

$$B_{0c}=\frac{1}{R_c}\sqrt{\frac{8\pi GmM_c}{\sigma_T}}=1283Gs$$

$$\Rightarrow \quad B=B_{0c}\frac{R_c}{R}\sqrt{\frac{M}{M_c}}$$

Seven planets of Trappist 1

- 2MASS J23062928-0502285 – TRAPPIST bESO. (TRAnsiting Planets and Planetesimals Small Telescope)
- 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 ± 0,007 of the solar mass, i.e. ~84 masses of Jupiter.
- The surface temperature is 2559 ± 50 К.
- 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

- Vida et al., 2017 analyzed the K2 light curve of the TRAPPIST-1 system. The Fourier analysis of the data suggests Prot = 3:2950:003 days. The light curve showed several flares, of which 42 events with integrated flare energies of 1.26*10^30 до 1.24* 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/Lbol= (2–4)×10^−4.
- There should be a stellar wind similar to the solar wind.

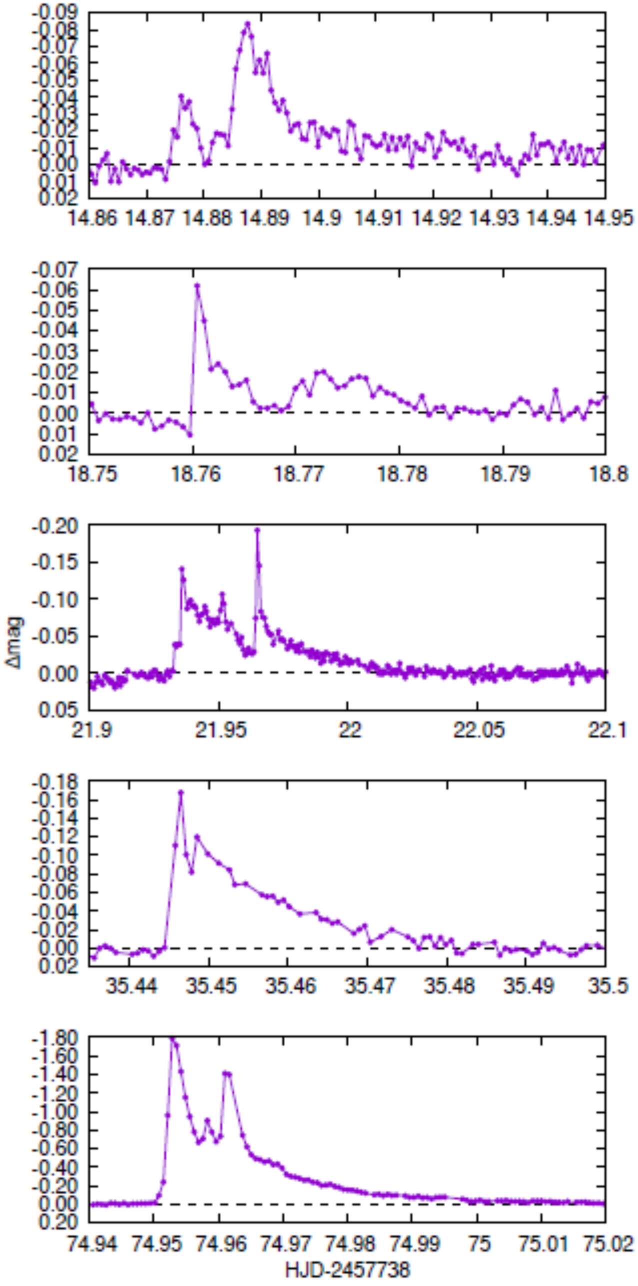


Figure 3. Light curves of the five complex flare events.

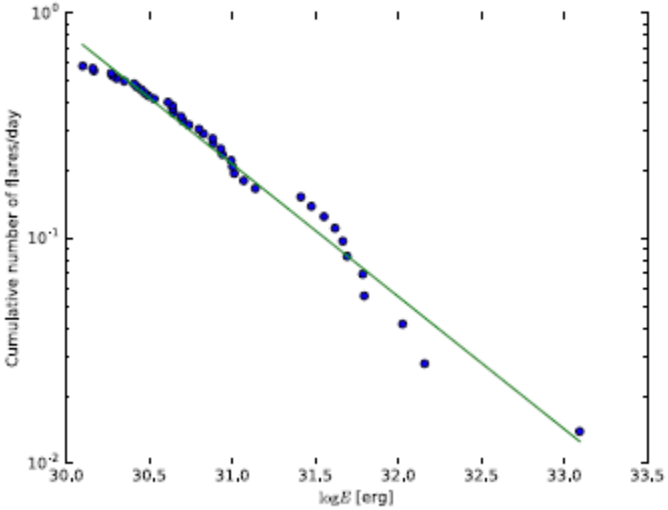


Figure 4. Cumulative flare frequency distribution fitted by a linear function

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*}=1.5·10^6 K

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

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

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

$$r1 = VT\frac{\varphi}{2\pi} = 0.82\ AU$$

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

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

*n=4652 cm**-3   V=442 km/s*

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

F, 0.0371 AU, fast wind

T_{c*}=3.8·10^6 K

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

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

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

$$r1 = VT\frac{\varphi}{2\pi} = 2\ AU$$

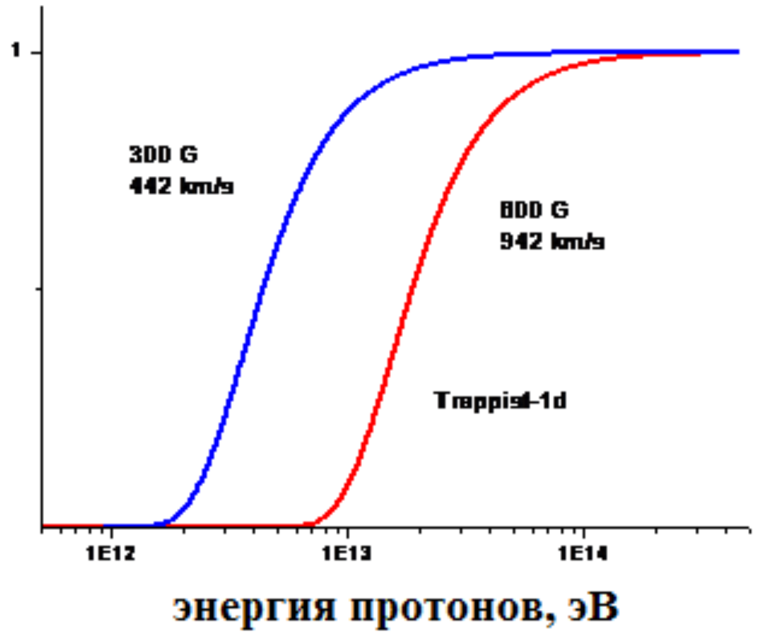
$$Q = -\frac{8\pi}{7} R_* k(T_{c*}) \cdot T_{c*} = -1.8\cdot 10^{28}\ \text{эрг/с}$$

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

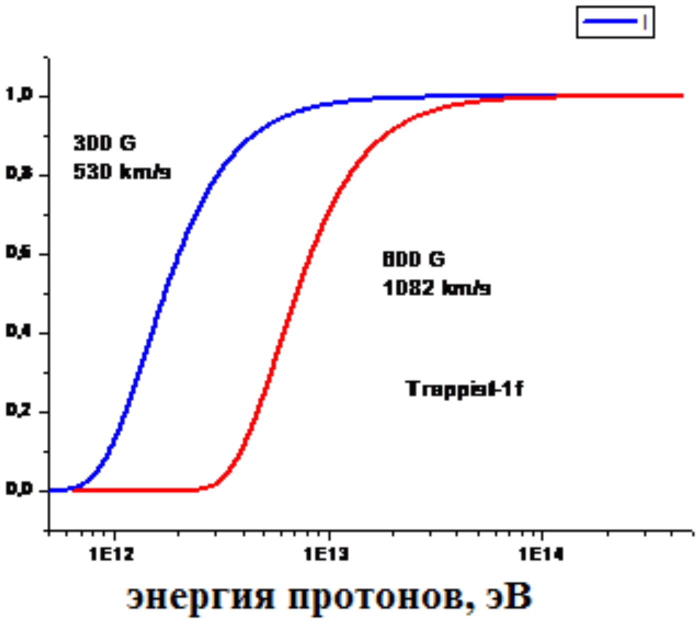
*n=4155 cm**-3   V=1082 km/s*

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

GCR modulation near Trappist-1d-f



Proton energy, eV



Proton energy, eV

Stellar CR. Trappist 1

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

$$U_{\max} = \alpha e E R = \alpha \beta \cdot 2550 GeV$$

Parameters of active region L=αR=α 8.510^9 cm;
$B = \beta B0 = 3000 \cdot \beta$ 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.
- Fluenses should be by 2-3 orders higher than in the largest Earth event of 775AD (8E10 cm**-2)
- Maximal intensities Imax=F/T should be 3-4orders 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 exoplanets.
- 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 Trappist 1 D and F 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.