# INVESTIGATION OF COSMIC RAY PROPAGATION IN INTERPLANETARY SPACE

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It was established experimentally that propagation of solar cosmic rays (scr) in interplanetary space up to 1 A.U. in most cases was of diffusion character ( Palmeira R.A.R., et al., 1971) .

In present paper we describe solar cosmic ray events on the basis of equation given in the paper of Dolginov A.Z., Toptygin I.N., 1966):

$$\frac{\partial n}{\partial t} = \frac{1}{r^2}\cdot\frac{\partial}{\partial r}\left[r^2\cdot\left(\varkappa_r\cdot\frac{\partial n}{\partial r} - n\cdot V\right)\right] + \frac{\partial}{\partial \mathcal{E}}\cdot\left\{\frac{2}{3}\cdot\frac{V}{r}\cdot\alpha\cdot\mathcal{E}\cdot n + D_{\mathcal{E}}\left[\frac{\partial n}{\partial \mathcal{E}} - \frac{n(E^2+P^2)}{E\cdot P^2}\right]\right\} \quad (1)$$

where n is density of particles in unit interval of kinetic energy $\mathcal{E}$ ,r - heliocentric distance, E and P -total energy and momentum of particle correspondinly, V - speed of solar wind, $\varkappa_r$ - coefficient of radial diffusion, $D_{\mathcal{E}}$ -coefficient of diffusion in space of energy, $\alpha=(2m_0c^2+\mathcal{E})/(m_0c^2+\mathcal{E})$, where $m_0c^2$ - energy at rest. Equation (1) describes process of diffusion propagation of charged component of solar cosmic rays including convecton, adiabatic cooling and statistical acceleration. Numerical solution of equation (1) was based on the grid technique ( Krylov V.I., et al., 1977 ).

Boundary conditions were taken in the form: $n(r,\mathcal{E},t)=0$; $CnV - \varkappa_r\frac{\partial n}{\partial r} = Q(\mathcal{E},t)$ at $r=r_s$ , where Q is function of source, C -Compton-Getting factor, $n(r_L,\mathcal{E},t)=0$, $r\in[r_s,r_L]$ ; $n(r,\mathcal{E}_1,t)=0$, $n(r,\mathcal{E}_2,t)\sim\mathcal{E}^{-\gamma_0}$ , $\mathcal{E}\in[\mathcal{E}_1,\mathcal{E}_2]$ .

As a test problem we solved equation (1) by Monte Carlo technique using transit moments of the first and second orders of the equation (1) which is equation of Fokker-Planck type ( Jokipii J.R., Levy E.H., 1977). Figure 1 shows calculated time-intensity profiles at 11 MeV at r=1 A.U.. Solid line represents the results of calculation by grid technique, histogram-Monte Carlo technique for the case of instantaneous injection of solar cosmic rays at point $r=0.01$ A.U. for $\gamma_0=3,5$, $r_L=6$ A.U., $\mathcal{E}_1=0,2$ MeV, $\mathcal{E}_2=50$ MeV, $\varkappa_r=\varkappa_0\mathcal{E}^{0.5}$, $\varkappa_0=$ $=const(r)$, $\varkappa_r(\mathcal{E}=11\text{ MeV})=1,16\times10^{21}$ cm$^2$/s, V=400 km/s.

Figure 2 shows calculated energy spectra $I_{t_m}$ obtained on the basis of maximum intensity at r=1 A.U., when $t=t_m$ and histogram represents the results of Monte Carlo technique, solid line -calculations by grid technique, dotted line shows the form of energy spectrum at source. The solid line at the bottom of figure 2 represents dependence of exponent $\gamma$ on $\mathcal{E}$ , when $I_{t_m}$ is approximated with the function of the form $\sim\mathcal{E}^{-\gamma}$ , dotted line is value of $\gamma_0$ . Hardening of scr energy spectrum at 1 A.U. is due to prevailing action of adiabatic cooling, when $D_{\mathcal{E}}=\alpha\frac{\mathcal{E}\cdot P^2}{E}\cdot\frac{\Delta U^2}{9\varkappa}$ ( Dolginov A.Z., Toptygin I.N., 1966), where $\Delta U=50$ km/s - speed of alfven waves in solar wind plasma at r=1 A.U..

The dotted line in figure 1 is a result of solution of the equation (1) for all similar parameters and conditions except suggestion that $\varkappa_r(\mathcal{E})$=const=1,16x$10^{21}$ $cm^2$/s. This condition is equvalent to $\gamma$=const(t). Good agreement in behaviour of I(t) was obtained for t>$t_m$ when $\gamma$=const(t) for $\varkappa_r \neq$const($\mathcal{E}$).

Usually when propagation of cosmic rays is investigated it is suggested that $\varkappa_r(r,\mathcal{E})=f(r)\Psi(\mathcal{E})$. To study validity of this suggestion we described experimental solar cosmic ray time-intensity profile for 28.05.67 and 02.11.69 events. The data were taken from the paper of Lanzerotti L.J. ,1975. Description was carried out by minimization the difference between experimental value of I(t) and theoretical ones. Minimization was carried out for scr at given energies in suggestion of instantaneous injection of particles and $r_L$=20 A.U., when $\varkappa_r=\varkappa_0 r^b$ at ranges $\varkappa_r$(r=1 A.U.) $\in$ [3,75x$10^{19}$ $cm^2$/s; 3,75x$10^{21}$ $cm^2$/s], b $\in$ [-2,2] with steps $\Delta\varkappa_0$= $0.1\cdot\varkappa_0^*$, $\Delta$b=0.5 , where $\varkappa_0^*$-previous value of $\varkappa_0$. Figure 3 shows obtained by minimization dependences $\lambda_r(\mathcal{E})$, b($\mathcal{E}$) for 28.05.67 event and dependences $\lambda_r$(R), b(R) for 02.11.69 event, where $\lambda_r$ -radial mean free path, R- rigidity of particle ( $\lambda_r=3\varkappa_r/V$ , V -particle speed ).

Figure 3a shows values of $\lambda_r(\mathcal{E})$ and $b(\mathcal{E})$ obtained by minimization of $\chi^2$(circles) and by least square method (rectangles) for $\gamma_0$=3 for protons at energy $\mathcal{E}$ : 1.2-2,4 MeV,2.5-4.3 MeV, 4.4-5.0 MeV; 5.0-9.4 MeV; 9.4-17.4 MeV; 16,5-19.7 MeV. Figure 3b shows $\lambda_r$(R) and b(R) for 02.11.69 obtained by mininmization using least square technique for electrons at energies: >0.35 MeV; >0.6 Mev; >1,1 MeV; for protons at energies: 1,1-2.5 MeV; 2,5-4.3 MeV; 5.0-8.8 MeV; 5.9-8.8 MeV, 8.8-16.7 MeV, 17.0-19,7 MeV; for alfa-particles at energies: 3.8-6.2 MeV; 6.2-8.5 MeV, 8.5-17.5 MeV, 17.5-24,5 MeV, 24.5-42.5 MeV, 42.5-83.5 MeV. Rhombs, circles and rectangles in the upper part of figure 3b are values of $\lambda_r$ for electrons,protons and alfa-particles correspondingly.

Analysis of figure 3 reveals that $\lambda_r \sim R^{\alpha}$ , $\alpha$=0,6 , $\alpha$=0,27 for events 28.05.67 and 02.11.69 correspondingly and $\partial b/\partial R$>0. Solid smooth curves in figure 4 show the results of description of time-intensity profile of scr protons for 28.05.67 for $\gamma_0$=2.3, $\varkappa_r=\varkappa_0 r^b \mathcal{E}^{\alpha}$ , $\alpha$=0.8, b=0.75$\cdot lg\,\mathcal{E}$ , [$\mathcal{E}$] = MeV. Coordinate axis for the given curve is shown with the help of arrow. Figures near curves are energy ranges of registration of solar cosmic rays. Solid line in figure 5 is description of energy spectrum of proton intensity $I_{t_m}(\mathcal{E})$ for the given event.

Pronounced softening of $I_{t_m}(\mathcal{E})$ at r=1A.U. ($I_{t_m}(\mathcal{E})\sim\mathcal{E}^{-2.6}$ ) with respect to scr spectrum at source where $I(t=0;r=r_s)\sim\mathcal{E}^{-1.8}$ should be noted.

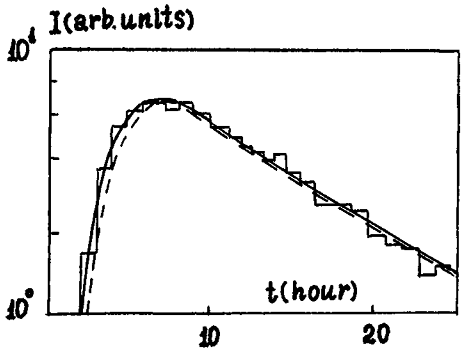


FIGURE 1.

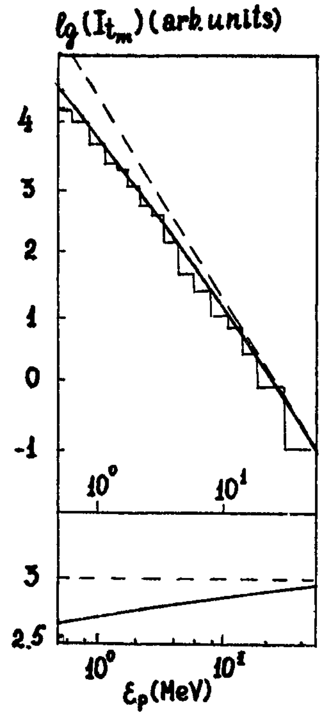


FIGURE 2.

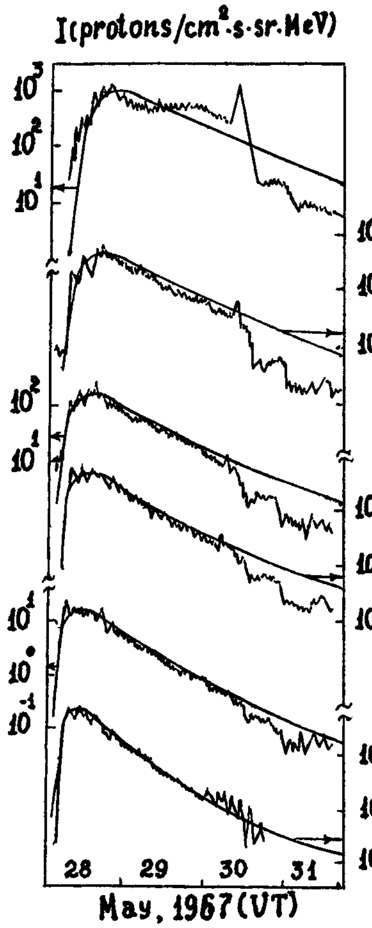


FIGURE 4.

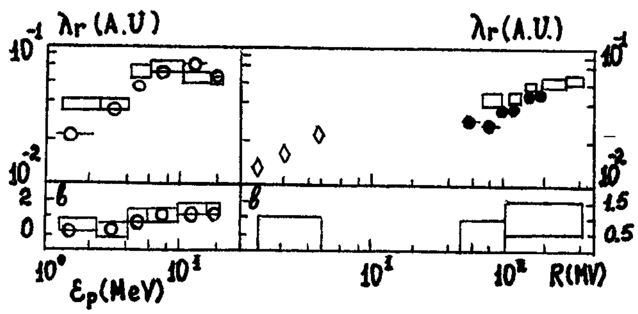


FIGURE 3.

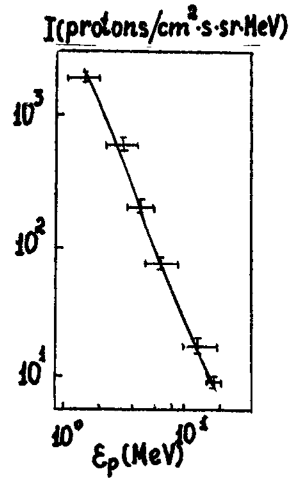


FIGURE 5.

Figure captions are given in the text.

Analysis of abovementioned results shows that suggestion of instantaneous injection allows to describe propagation of scr when function $\varkappa_r(r,R)$ can not be factorized with respect to r and R and of $\varkappa_r \sim r^b R^\alpha$ ,then $\partial b/\partial R > 0$ and at r=1 A.U. $\alpha$=0.3-0.6 that is in good agreement with the data on frequency power spectrum of interplanetary magnetic field fluctuation.

REFERENCES

Dolginov A.Z., Toptygin I.N., ZHETF,1966,v.51,p.1771-1783.
Jokipii J.R.,Levy E.H., Astrophys. J.,1977,v.213, p.L85-L88.
Kolomeets E.V., Sevos'tyanov V.N., Stekol'nikov N.V.,17 ICRC, 1981, v.3, p.322-325.
Krylov V.I.,Bobkov V.V.,Monastyrsky P.I. Vychislitel'nye metody, M., 1977, v.2, p.155.
Lanzerotti L.J. YII Leninrgrad Mezhdun. Sem.,L., p.161.
Palmeira R.A.R., et al., Leningrad Mezhdun. Sem., 1971,p. 76-151.