THE ROLE OF SHOCK WAVES IN MODULATION OF GALACTIC COSMIC RAYS

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INTRODUCTION

In the last decade our understanding of modulation of the galactic cosmic rays has considerably progressed by the exploration by space probes of mayor heliospheric structures, such as the Coratating Interaction Regions, the neutral sheet, and the compression regions of intense heliospheric magnetic fields. Also relevant in this context were the detections in the outer heliosphere of long lasting Forbush type decreases of cosmic ray intensity (1,2,3).

In this paper we shall present the results of our recent theoretical studies on the changes in intensity and energy, at different locations from the sun, induced by the passage of shocks across the heliosphere. In this short version of our research we shall deal mainly with the simplest cases of modulation of 1GV and 2GV particles by single or several shocks during periods of positive and negative solar field polarity.

We shall report here the results of the theoretical aspects of our research. The comparison of the theoretical predictions with space probe data (4,5) will allow us to draw conclusions on the role of shocks on the modulation on both the 11 and 22 year galactic cosmic ray cycles in the outer heliosphere and on the plausibity of the models and parameters used.

METHOD AND MODELS

The modulation that the galactic relativistic cosmic rays undergo during their propagation across the heliosphere all the way to the observer, is studied by means of Liouville's theorem that states that the six dimensional phase space density $f(\underline{r},\underline{p})$ is conserved along the particle trajectories. In order to follow the past history of a particle of momentum $\underline{p}$, detected at $\underline{r}$, one must trace the trajectory of the particle all the way to the boundary.

The method which we used in our studies of shock induced Forbush Decreases (6,7),(the FdM method), consists of integration of full differential equation of motion $d\underline{p}/dt = e(\underline{E}+\underline{v}x\underline{B}/c)$ of a large mumber of particles moving in both Parkerian and magnetic field shock model, scattered also by small irregularities achieved by random angular deflection corresponding to a chosen diffusion coefficient. The trajectory of each individual particle is integrated back in time, all the way from the observer at $\underline{r}$ to the chosen spherical boundary, keeping all along a detailed account, of the changing particle momentum. Tne intensity of the particle is inferred from the relation $j = fp^2$. We determine the associated intensity at the boundary by a power law in total particle energy of spectral index -2.6.

The FdM method allowed us to prove that the principal mechanism of Forbush decreases is simply the additional adiabatic cooling of the relativistic cosmic rays during their prolongued containment by magnetic field between the shock and the sun.

In the present research we use a method designed by B. Thomas (the BTM -

method wich saves much computer time. It differs from FdM in that instead of solving the full differential equation we now solve the Boltzman equation and deal with the GC. We compute the focussing and all the drift velocities and evaluate the diffusion and the energy loss by the FdM method. Just as in FdM we impose a $k_{\parallel}$ and $k_{\perp}$ and follow the trajectory integration of 50 particles, back in time, from the position of the observer all the way to the boundary; at every step size of the integration we compute the "average particle" position and pitch angle.

The momentum p_o at the boundary, averaged over all individual particles estimates is used to compute the intensity and particle energy loss at r. (For better understanding of FbM and TBM methods we refer the reader to reference 7)

We use the semispherical shock model of Dryer's type (8), a Parkerian magnetic field model autside the shocks, and a magnetic field model inside the shock, given by $B = B_o/r^2$; $B\phi=(B_o/r)V_w\Omega\sin\Theta\{3+3\cos\pi(r-r_o)/d\}$, where d is the width of the shock and r_o is the heliospheric distance of the shock interface.

In our elementary studies on the shocks influence of cosmic ray modulation we asume that all the shocks propagate with the same velocity of 400 klm/sec, its width changing with the position of the shock, given by $d=0.2xr_o$. The shocks are placed at sufficiently large distance, (20AU), from each other to avoid shock-shock interaction. Moreover the shock's loss of energy is not considered. A flat ecliptic neutral sheet model is used; we place the observers at $\lambda=0, \varphi=0$ and $\lambda=5°, \varphi=0°$, for positive and negative polarity periods, respectively.

RESULTS AND COMMENTS

Figure 1A exhibits the 22 years modulation of 1GV protons in the outer heliosphere induced by the diffusive propagation in a merely Parkerian magnetic field; $k_{\parallel}=.219\times10^{21}r\ cm^2/sec$ and $7.68\times10^{21}r cm^2/sec$, for 1 and 2GV respectively. As seen by observers located at different r, the intensities for negative polarity are not only higher that for positive polarity, but exhibit a relatively constant radial gradient. In the table below we list some of the modulation characteristics.

1	2	3	- 4	+
1GV	80 UA: 42% 20 UA: 2.4%	0.7%/AU	25%	41.9%
2GV	80 UA: 30% 29 UA: 21%	.16%/AU	3.5%	9.1%

1. Proton rigidity.
2. The % ratio of negative to positive polarity intensities at 80 and 20 UA
3. Average intensity gradient of $20<r<80$ AU (negative polarity)
4. % of total energy (E_T) loss by adiabatic cooling for 20 AU observer.

Obviously the theoretical data on propagation in Parkerian field is rather elementary as it does not include the effects induced by large magnetic heliospheric structures. Still it serves as a uselfull tool, as a first approximation, to which the effect of shocks, CIR or inclined neutral sheet can be separately added.

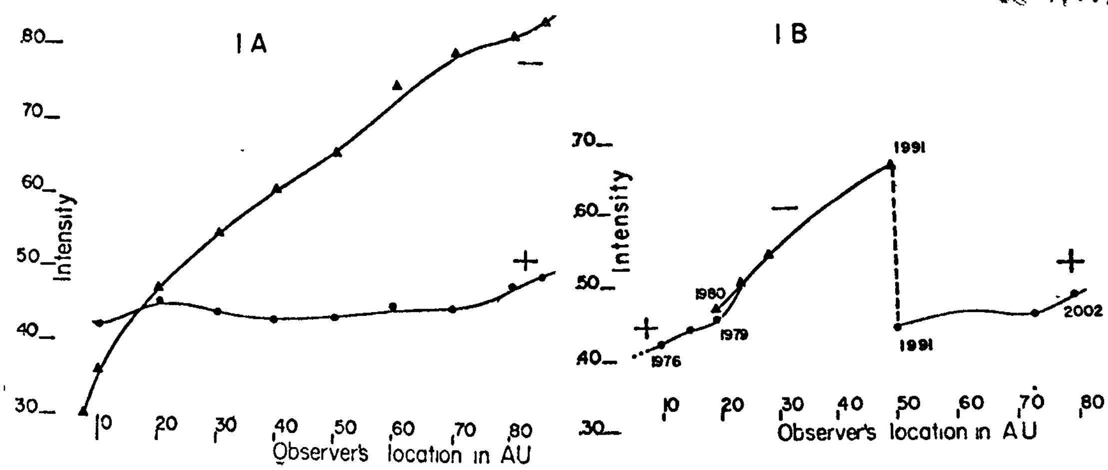


Fig.1A: Intensity of 1GV protons, detected by observers located along the cliptic at different distances from the sun, for A- and A+ periods.

Fig.1B: The computed intensities of 1GV protons for 1976-2002 period. The sign of solar field polarity is marked.

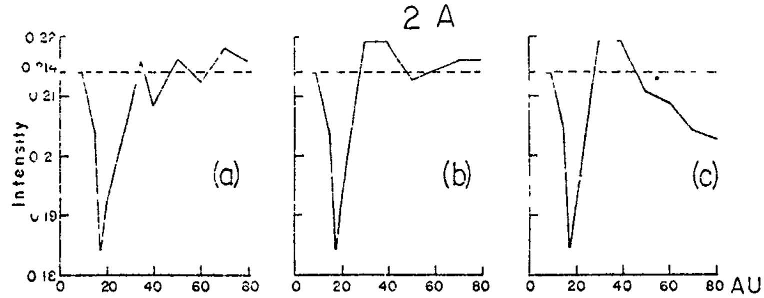
Finally we shall discuss the modulation of cosmic rays induced by -- shocks. Using the BTM method and the shock and shock associated magnetic-field models, se have computed the intensities of 2 GV protons for the -- cases of 1, 2, and 4 shocks propagating across the outer heliosphere. -- Notice that it takes aproximately 1J months for the shocks to propagate - from the sun to the boundery. For the period of positive solar field polarity. An observer located at 17 AU will detect as illustrated in Fig.2A a similar pattern of intensity vs time, for the three cases mentioned. A-typical Forbush type 15% intensity decrease, lasting aproximately 100 days of equal decrease and recovery time, followed by a 40 days period of 5% - intensity increase above the Parkerian propagation intensity level (which we shall call here PI). This increase is due to an acceleration,during -- the temporal trapping of particles between the shocks is followed by a recovery to practicaly PI level. Only in the case of 4 shocks one detects as slow intensity decrease of less than 4%.

Thes intensity vs time pattern, during A- period is very different from the one described above, which obviously implies an important 22 years -- cosmic rays intensity cycle.

As seen in figure 2B, the observer at 24 AU, sees a slight increase of-intensity, lasting 40 and 80 days for 1 shock and 2 shocks, respectively; this is probably due to the typical PI increase during the A- periods.

This increase is followed by an abrupt 50% decrease that occurs at 30-AU for the case of 1 shock and at 50 AU for 2 shocks propagating across - the outer heliosphere. Necesarily the intensity level will rise as the - particles aproach the vecinity of the boundary.

One must keep in mind that the pattern I vs t used, corresponds to a -- rather simple model of shocks, described before. We plan to continue -- this research using a much more realistic shock models.



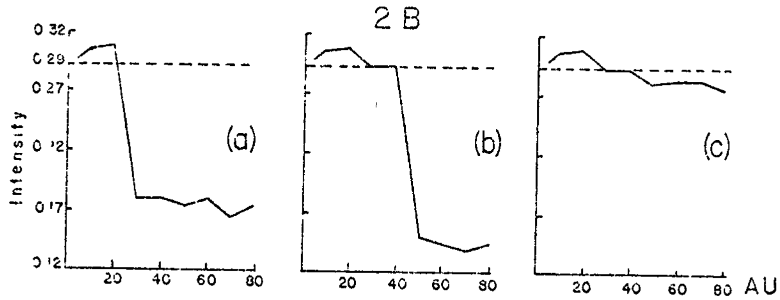


Fig.2A and 2B show the intensity variations during 340 days of observations by an observer located along the ecliptic at fixed distance from the sun. The variations are induced by one(a),two(b)or four(c)shocks. The abcissa-marks the position r_o of the most advanced shock; it also provides the -- time:(t)x4.33 r_o days, measured from the day of emision of the mentioned-shock. (Fig.2A: observer at 17 AU, A-; Fig.2B observer at 24 AU, A+)

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