Solar Modulation of Cosmic Rays

Summer internship - LIP

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The solar cycle or solar magnetic activity cycle is the nearly periodic 11-year change in the Sun's activity and appearance.

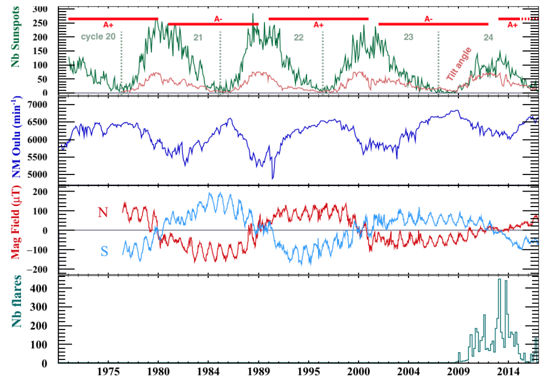

Figure: Experimental data of the solar cycle registered until 2017.

The solar wind, emanating from the Sun, creates a bubble that extends far past the orbits of the planets. This consists on a dipole structure, meaning that the magnetic field lines have opposite directions in each hemisphere. Generating a structure called the heliospheric current sheet.

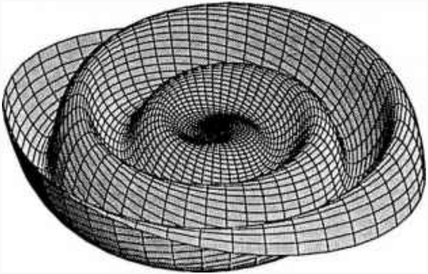

Figure: Heliospheric current sheet.

Cosmic-ray propagation inside the heliosphere is described by the Parker equation.

$$-\mathbf{V} \cdot \vec{\nabla} f + \vec{\nabla} \cdot (\mathbf{K} \cdot \vec{\nabla} f) + \frac{1}{3}(\vec{\nabla} \cdot \mathbf{V}) \frac{\partial f}{\partial \ln p} = \frac{\partial f}{\partial t}$$

The following effects are accounted:

- Convection and drift
- Diffusion
- Adiabatic energy loss

The original equation consists in a five-dimensional solution (three spacial coordinates plus momentum and time).

Considering the following approximations:

I No sources of cosmic rays
II Steady state $\frac{\partial}{\partial t} = 0$
III Spherical symmetry

We solved the equation using a 2-dimension approach: in order of radius [r] and rigidity [p].

$$-V\cdot\frac{\partial f}{\partial r}+\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2K\frac{\partial f}{\partial r}\right)+\frac{1}{3r^2}\frac{\partial}{\partial r}(r^2V)\frac{\partial f}{\partial \ln p}=0$$

$$V=400[kms^{-1}]$$

$$K=4.38\times10^{18}\beta\frac{p}{1\times10^3}[m^2/s]$$

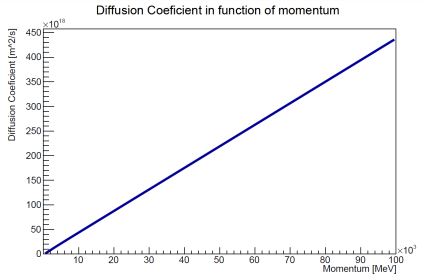

Figure: Diffusion Coefficient $[0,1\times10^5]$ MeV

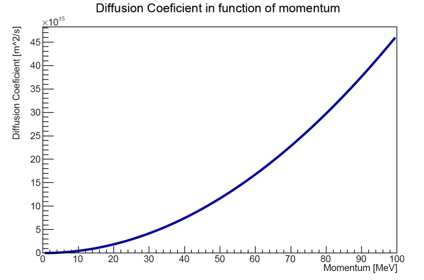

Figure: Diffusion Coefficient $[0,1\times10^2]$ MeV

$$f(r,p) = P_1 f(r-\Delta r, p) + P_2 f(r+\Delta r, p) + P_3 f(r, p+\Delta \ln p)$$

- Equation solved using the Crank Nicholson method

- Discretization of the problem using code written in c++

- Application of the stochastic method to the solution

- Determine the variation of the intensity of cosmic rays with momentum and radial distance to the sun

$$P_1 = \frac{\alpha+\beta}{\alpha+2\beta+\gamma}$$

$$P_2 = \frac{\beta}{\alpha+2\beta+\gamma}$$

$$P_3 = \frac{\gamma}{\alpha+2\beta+\gamma}$$

$$\alpha = 3\Delta r \Delta \ln p (2K - rV)$$

$$\beta = -3rK\Delta \ln p$$

$$\gamma = -2V\Delta r^2$$

Random Walk:

* Backward in radius if the r.n. is below P_1;
* Forward in radius if the r.n. is between P_1 and P_2;
* Backward in momentum if the r.n. is above P_3.

1000 pseudo-particles generated

The final position of each is registered and based on the number of times they reached the boundaries (adding all the registered values and dividing by the number of pseudo-particles) we obtain the intensity value of that position.

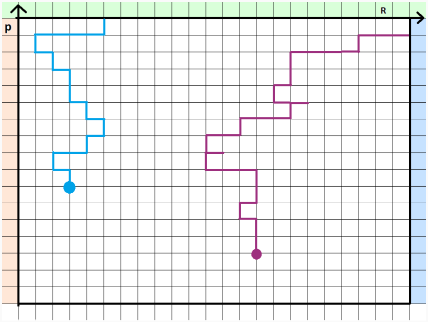

Figure: Example of the path grid used in the stochastic method.

1. At 90 AU from the sun, the flux of Cosmic Ray Protons is modulated according to the figure (right boundary):

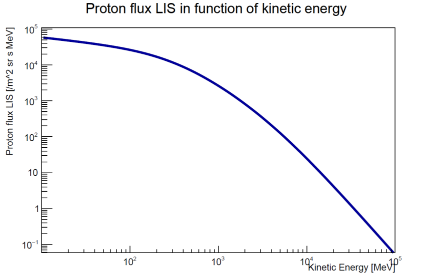

Figure: Intensity Spectra of Galactic Cosmic Ray Protons using a local interstellar spectrum (LIS).

2. At the radius of the sun, the flux is approximately zero (left boundary).
3. For higher energies, at 1×10^5 MeV momentum, there is no modulation of the cosmic rays as shown in the figure: $U_p = 0.0532667[par/m^2 \cdot s \cdot sr \cdot MeV]$

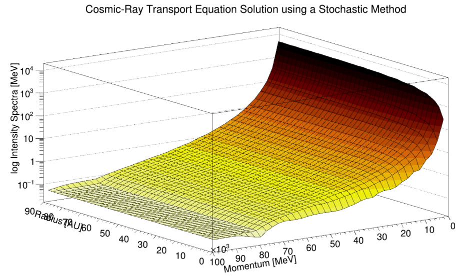

Figure: Intensity spectra of cosmic rays with momentum and radial distance from the sun.

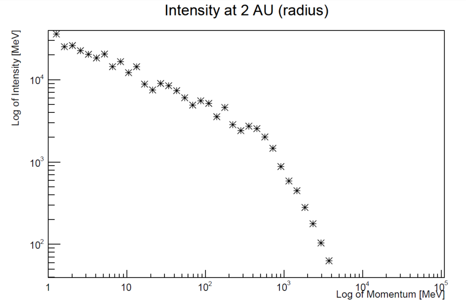

Figure: Intensity spectra of cosmic rays at 2 AU from the sun.

I Intensity at 1 UA to compare with results

II Parallel computation

III Solving the equation with more dimensions

References

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