Modelling of cosmic ray modulation in the heliosphere by stochastic processes

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Research is what I'm doing when I don't know what I'm doing.
- Wernher von Braun

To Zannélize - My wife, companion and friend.

Abstract

The transport of cosmic rays in the heliosphere is studied by making use of a newly developed modulation model. This model employes stochastic differential equations to numerically solve the relevant transport equation, making use of this approach's numerical advantages as well as the opportunity to extract additional information regarding cosmic ray transport and the processes responsible for it. The propagation times and energy losses of galactic electrons and protons are calculated for different drift cycles. It is confirmed that protons and electrons lose the same amount of rigidity when they experience the same transport processes. These particles spend more time in the heliosphere, and also lose more energy, in the drift cycle where they drift towards Earth mainly along the heliospheric current sheet. The propagation times of galactic protons from the heliopause to Earth are calculated for increasing heliospheric tilt angles and it is found that current sheet drift becomes less effective with increasing solar activity. Comparing calculated propagation times of Jovian electrons with observations, the transport parameters are constrained to find that $\sim 50\%$ of 6 MeV electrons measured at Earth are of Jovian origin. Charge-sign dependent modulation is modelled by simulating the proton to anti-proton ratio at Earth and comparing the results to recent PAMELA observations. A hybrid cosmic ray modulation model is constructed by coupling the numerical modulation model to the heliospheric environment as simulated by a magneto-hydrodynamic model. Using this model, it is shown that cosmic ray modulation persists beyond the heliopause. The level of modulation in this region is found to exhibit solar cycle related changes and, more importantly, is independent of the magnitude of the individual diffusion coefficients, but is rather determined by the ratio of parallel to perpendicular diffusion.

Keywords: `Cosmic rays, heliosphere, magneto-hydrodynamics, stochastic differential equations, Jovian electrons, charge-sign dependent modulation, heliopause, heliospheric current sheet, propagation times, particle drifts, energy losses`

Opsomming

Die transport van kosmiese strale in die heliosfeer word bestudeer deur gebruik te maak van 'n nuut ontwikkelde modulasie model. Die model gebruik stogastiese differensiaalvergelykings om die relevante transportvergelyking numeries op te los, deur gebruik te maak van die model se numeriese voordele, asook die geleentheid om addisionele inligting aangaande die modulasieproses te verkry. Die voortplantingstye en energieverliese van galaktiese elektrone en protone word bereken vir verskille dryfsiklusse. Dit word bevestig dat protone en elektrone dieselfde hoeveelheid styfheid verloor indien hulle dieselfde transportkoëffisiente ervaar. Die deeltjies spandeer meer tyd in die heliosfeer, en verloor meer energie, in die dryfsiklus waar hulle meestal langs die heliosferiese neutrale vlak na die Aarde dryf. Die voortplantingstye van galaktiese protone van die heliopouse na die Aarde word bereken vir toenemende waardes van die heliosferiese kantelhoek en daar word gevind dat die effektiwiteit van neutrale vlak dryf afneem met toenemende sonaktiwiteit. Deur berekende en waargenome waardes van die voortplantingstyd van Jupiterelektrone met mekaar te vergelyk, word die transportparameters sodoende beperk om te bepaal dat $\sim 50\%$ van 6 MeV elektrone, soos by die Aarde waargeneem, vanaf Jupiter afkomstig is. Ladingsafhanklike modulasie is gesimuleer by die Aarde deur die proton en anti-proton verhouding te bereken en te vergelyk met onlangse PAMELA waarnemings. 'n Hibriede modulasiemodel word gekonstrueer deur die numeriese modulasiemodel te koppel aan die heliosferiese omgewing soos gesimuleer deur 'n magneto-hidrodinamiese model. Deur van die model gebruik te maak, word gewys dat modulasie verby die heliopouse plaasvind. Die vlak van modulasie in die gebied toon ook sonaktiwiteits-gekoppelde veranderinge en is, van meer belang, onafhanklik van die grootte van die individuele diffusie koëffisiente maar word bepaal deur die verhouding van parallelle tot loodregte diffusie.

Sleutelwoorde: `kosmiese strale, heliosfeer, magneto-hidrodinamika, stogastiese differentiaalvergelykings, Jupiter elektrone, ladingsafhanklike modulasie, heliopouse, heliosferiese neutrale vlak, voortplantingstye, deeltjie dryf, energie verliese`

Acronyms and Abbreviations

Listed below are the acronyms and abbreviations used in the text. For the purpose of clarity, any such usages are written out in full when they first appear.

1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional
AU	Astronomical Unit[1]
BS	Bow Shock
CR	Cosmic Ray
CT	Constraint Transport
eV	Electron volt[2]
Fermi I	First order Fermi (diffusive shock) acceleration
Fermi II	Second order Fermi (stochastic) acceleration (diffusion in momentum space)
GCR	Galactic Cosmic Ray
HCS	Heliospheric Current Sheet
HMF	Heliospheric Magnetic Field
HP	Heliopause
IBEX	Interstellar Boundary Explorer
ISM	Interstellar medium
LIS	Local Interstellar Spectrum
MHD	Magneto-hydrodynamic
PAMELA	Payload for Antimatter Exploration and Light-nuclei Astrophysics
PRN	Pseudo Random Number
PRNG	Pseudo Random Number Generator
PUs	Program Units
SDE	Stochastic Differential Equation
TPE	Parker Transport Equation
TS	Termination Shock
V1	Voyager 1
V2	Voyager 2

[1]Defined to be the average distance between the Sun and Earth; 1 AU = 1.496×10^8km.
[2]1 eV = 1.6×10^{-19} J (10^3 eV = 1 keV, 10^6 eV = 1 MeV, 10^9 eV = 1 GeV)

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