Time-dependent modulation of cosmic rays in the outer heliosphere

Rex Manuel

Time-dependent modulation of cosmic rays in the outer heliosphere

Rex Manuel, M.Sc
21245274

Thesis accepted for the degree Doctor of Philosophy in Physics at the North-West University, Potchefstroom Campus, South Africa

Supervisor: Prof. S. E. S. Ferreira
Co-supervisor: Prof. M. S. Potgieter

February 2013
Potchefstroom
South Africa

Live as if you were to die tomorrow. Learn as if you were to live forever.
- Mahatma Gandhi

Not all of us can do great things. But we can do small things with great love.
- Mother Teresa

With determined efforts you can always succeed against established beliefs.
- A P J Abdul Kalam

This work is dedicated to
my mom (Roselind) - For all her love and sacrifice.

Abstract

The time-dependent modulation of galactic cosmic rays in the heliosphere is studied by computing intensities using a two-dimensional, time-dependent modulation model. The compound approach of *Ferreira and Potgieter* (2004), which describes changes in the cosmic ray transport coefficients over a solar cycle, is improved by introducing recent theoretical advances in the model. Computed intensities are compared with Voyager 1 and 2, IMP 8 and Ulysses proton observations in search of compatibility. It is shown that this approach gives realistic cosmic ray proton intensities on a global scale at Earth and along both Voyager spacecraft trajectories. The results show that cosmic ray modulation, in particular during the present polarity cycle, is not just determined by changes in the drift coefficient but is also dependent on changes in the diffusion coefficients. Furthermore, a comparison of computations to observations along the Voyager 1 and Voyager 2 trajectories illustrates that the heliosphere is asymmetrical. Assuming the latter, $E > 70$ MeV and 133-242 MeV cosmic ray proton intensities along Voyager 1 and 2 trajectories are predicted from 2012 onwards. It is shown that the computed intensities along Voyager 1 can increase with an almost constant rate since the spacecraft is close to the heliopause. However, the model shows that Voyager 2 is still under the influence of temporal solar activity changes because of the relatively large distance to the heliopause when compared to Voyager 1. Along the Voyager 2 trajectory the intensities should remain generally constant for the next few years and then should start to steadily increase. It is also found that without knowing the exact location of heliopause and transport parameters one cannot conclude anything about local interstellar spectra. The effect of a dynamic inner heliosheath width on cosmic ray modulation is also studied by implementing a time-dependent termination shock position in the model. This does not lead to improved compatibility with spacecraft observations so that a time-dependent termination shock along with a time-dependent heliopause position is required. The variation of the heliopause position over a solar cycle is found to be smaller compared to that of the termination shock. The model predicts the heliopause and termination shock positions along Voyager 1 in 2012 at ~119 AU and ~88 AU respectively and along Voyager 2 at ~100 AU and ~84 AU respectively.

Keywords: Cosmic rays, solar cycle, solar modulation, solar activity, compound approach, heliosphere, heliopause, Voyager spacecraft

Opsomming

Die tydsafhanklike modulasie van galaktiese kosmiese strale in die heliosfeer word bestudeer deur van 'n twee-dimensionele tydsafhanklike modulasie model gebruik te maak om intensiteite te bereken. Die saamgestelde benadering van Ferreira en Potgieter (2004), wat die tydsafhanklikheid van die transportmeganismes oor 'n sonsiklus beskryf, word uitgebrei deur die nuutste teoretiese verwikkelinge in ag te neem. Die berekende intensiteite word vergelyk met Voyager 1 en 2, IMP 8 en Ulysses ruimtetuig waarnemings. Daar word gewys dat die benadering realistiese kosmiese straal proton intensiteite by die Aarde en langs beide Voyager ruimtetuig trajekte bereken. Die resultaat wys daarop dat die modulasie van kosmiese strale, veral in die huidige polariteit siklus, nie net bepaal word deur veranderings in die dryf koëffisiënt nie, maar ook deur veranderings in die diffusie koëffisiënt. Deur berekeninge met waarnemings langs beide Voyager 1 en 2 trajekte te vergelyk, word daar verder getoon dat die heliosfeer asimmetries is. Deur die kenmerk in ag te neem word $E > 70$ MeV en 133-242 MeV kosmiese straal proton intensiteite langs beide Voyager 1 en 2 trajekte voorspel vanaf 2012. Daar word gewys dat die berekende intensiteite langs Voyager 1 se trajek 'n toename teen 'n konstante tempo toon omdat die ruimtetuig naby die modulasiegrens is. Die model wys ook daarop dat Voyager 2 se waarnemings nog steeds onder die invloed van sonaktiwiteit is omrede die relatiewe groter afstand na die modulasiegrens in vergelyking met Voyager 1. Langs Voyager 2 se trajek gaan die intensiteite byna konstant bly vir die volgende paar jare waarna dit geleidelik sal begin toeneem. Daar word ook gewys dat as die presiese posisie van die modulasie grens en die transportmeganismes onbekend is daar nie uitspraak gelewer kan word oor die lokale interstellêre spektrum nie. Die effek van 'n dinamiese helioskede op kosmiese strale word bereken deur 'n tydsafhanklike terminasie skok posisie in die model te implementeer. Die lei nie noodwendig na beter vergelykbaarheid met die waarnemings nie en 'n tydsafhanklike modulasiegrens word ook benodig. Daar word gevind dat die variasie van die modulasiegrens oor 'n sonsiklus kleiner is as die van die terminasie skok. Die model voorspel dat die modulasiegrens en die terminasie skok se posisies langs Voyager 1 se trajek in 2012 by $\sim$119 AU en $\sim$88 AU onderskeidelik is en langs Voyager 2 se trajek by $\sim$100 AU en $\sim$84 AU onderskeidelik is.

Sleutelwoorde: Kosmiese strale, sonsiklus, modulasie, sonaktiwiteit, saamgestelde benadering, heliosfeer, modulasie grens, Voyager ruimtetuig.

Nomenclature

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
ADI	Alternating direction implicit
AU	Astronomical unit (1 AU = 149.6×10^9 m)
CIR	Corotating interaction region
CME	Coronal mass ejection
DT	Damping model
eV	Electron volt (1 eV = 1.6×10^{-19} J)
FLS	Fast latitude scan
GMIR	Global merged interaction region
HCS	Heliospheric current sheet
HMF	Heliospheric magnetic field
HPS	Heliopause spectrum
IMP	International Monitoring Platform
ISMF	Interstellar magnetic field
KET	Kiel Electron Telescope
LIS	Local interstellar spectra
LISM	Local interstellar medium
MHD	Magnetohydrodynamic
MIR	Merged interaction region
QLT	Quasilinear theory
RS	Random sweeping model
TPE	Transport equation
TS	Termination shock
WCS	Wavy current sheet

Contents