Time-dependent modulation of cosmic rays in the outer heliosphere

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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 $\sim$119 AU and $\sim$88 AU respectively and along Voyager 2 at $\sim$100 AU and $\sim$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

Chapter 1

Introduction

Galactic cosmic rays are charged particles entering the heliosphere from the galaxy. As they enter, these particles encounter the solar wind and the embedded heliospheric magnetic field. This interaction causes the intensities of these particles to change as a function of position, energy and time, a process called the modulation of cosmic rays. When cosmic rays enter the heliosphere they experience four major modulation processes, namely (1) convection, due to the expanding solar wind, (2) energy changes such as adiabatic cooling, diffusive shock acceleration and continuous acceleration e.g. heating or stochastic acceleration, (3) diffusion, random walks along and across the turbulent heliospheric magnetic field, and (4) drift effects due to gradient and curvatures in heliospheric magnetic field or any abrupt changes in the field direction such as the current sheet.

Cosmic ray transport is influenced by solar activity and this leads to ∼11 year and ∼22 year modulation cycles in the cosmic ray intensities. The aim of this study is to compute time-dependent modulation of galactic cosmic rays in the inner and the outer heliosphere over various solar cycles using a numerical model. Results from this model are compared to different spacecraft observations, in particular cosmic ray observations on-board both Voyager spacecraft. This topic is relevant since both the Voyager spacecraft are in the inner heliosheath region and close to the heliopause providing in-situ observations.

A state of the art 2D time-dependent numerical model (see Chapter 4) originally developed by *Le Roux* (1990) and *Potgieter and Le Roux* (1992), which solves the *Parker* (1965) transport equation, is used for this study. This numerical model was further improved by *Ferreira* (2002) and *Ferreira and Potgieter* (2004) considering the time-dependent global changes in the heliospheric magnetic field and tilt angle to empirically construct a time-dependence in transport coefficients. This approach is called the compound approach (see Chapter 5) and was applied by *Ndiitwani* (2005) and *Magidimisha* (2011) to calculate cosmic ray intensities in the inner heliosphere.

In this study the compound approach is improved by introducing recent theoretical advances in transport coefficients by *Teufel and Schlickeiser* (2002, 2003), *Shalchi et al.* (2004) and *Minnie et al.* (2007). This modified compound approach uses the magnetic field magnitude, statistical magnetic field variance and tilt angle as input parameters (see Chapter 6) to construct a time-dependence in the transport parameters related to these recent theoretical studies. These time-dependent changes in the parameters are then transported with the solar wind speed in the simulated heliosphere to compute cosmic ray intensities at Earth and along both the Voyager spacecraft trajectories. The $E > 70$ MeV and 133-242 MeV proton observations on-board both Voyagers are compared to the computed 2.5 GV (∼1.8 GeV) and 200 MeV proton intensities along the Voyager spacecraft trajectories. For the inner heliosphere, the computed 2.5 GV intensities at Earth are compared to $E > 70$ MeV proton observations on-board IMP 8 and ∼2.5 GV proton observations on-board Ulysses.

It will be shown in Chapter 6 that this new approach gives compatible intensities on a global scale when compared to spacecraft observations. However, after ∼2004, the model fails to reproduce the observations at Earth, suggesting a further improvement to the assumed time-dependence in the transport coefficients. The time-dependence in the parallel and perpendicular diffusion coefficients, as suggested by recent theoretical advances, is modified in Chapter 7 which leads to compatible modelling results along the Voyager 1 trajectory and at Earth on a global scale. This new approach also compares well to the previous compound approach of *Ferreira* (2002) and *Ferreira and Potgieter* (2004). It is shown that when this new approach is assumed, cosmic ray modulation is no longer largely determined by changes in the drift coefficient but also by solar cycle related changes in the diffusion coefficients, especially for the present polarity cycle.

The study of cosmic ray intensities along the Voyager 1 and Voyager 2 spacecraft trajectories is presented in Chapter 8. It is suggested that different transport parameters along the Voyager 1 and Voyager 2 trajectories are not sufficient to reproduce the cosmic ray observations, and an asymmetry in the assumed heliospheric geometry is necessary. Also, by extrapolating the input parameters in time, predictions for $E > 70$ MeV and 133-242 MeV cosmic ray proton intensities along the Voyager 1 and Voyager 2 trajectories are presented in Chapter 9. The computed results show that the Voyager 1 intensities should increase at a constant rate due to its proximity to the heliopause, but Voyager 2 intensities should still show the influence of temporal changes in solar activity due to the larger distance to the heliopause compared to Voyager 1. The study also reveals that a conclusion on a heliopause spectrum, and in particular a local interstellar spectrum, is not possible without knowing the exact location of the heliopause, the modulation boundary and the transport parameters.

Finally, the study investigates the effect of a dynamic inner heliosheath on cosmic ray intensities along both Voyager trajectories. In Chapter 10 a time-dependent termination shock position is implemented in the model assuming the termination shock position profiles as proposed by *Snyman* (2007) and *Webber and Intriligator* (2011) along both the Voyager trajectories. The computed intensities, when compared to observations, show that a time-dependent termination shock profile alone in the model does not lead to improved compatibility (as shown in Chapter 9), but a time-dependent termination shock position along with a time-dependent heliopause position is required. The modelling results show that the excursions of the heliopause position over a solar cycle are smaller than the excursions of termination shock position. The study also suggests that the ratio between the heliopause distance and termination shock distance fluctuates over a solar cycle. The ratio along the Voyager 1 trajectory was also found to be larger than along the Voyager 2 trajectory, possibly due to a heliospheric asymmetry.

Extracts from this work were published in peer reviewed journals. See *Manuel et al.* (2011a) and *Manuel et al.* (2011c).