

Chapter 1

Introduction

The transport of cosmic rays (CRs) through the heliosphere is largely governed by the well known *Parker* [1965] transport equation. Because of the complexity of this equation, it must be solved numerically. In this thesis, such a numerical modulation model is constructed and used to study the transport of CRs in the heliosphere.

The structure of this thesis is as follows:

Chapter 2 introduces the reader to the basic concepts related to CRs, the heliosphere and the transport of CRs in the heliosphere. The structures present in the heliosphere are discussed, including the solar wind, the heliospheric magnetic field and the heliospheric current sheet. CR origin and classification are briefly discussed, followed by the relevant transport equation. The different processes including in this equation are also introduced. Selected temporal variations of the heliospheric environment are shown, as well as the effects thereof on cosmic ray intensities as observed at Earth.

The three-dimensional (3D) magneto-hydrodynamic model of *Pen et al.* [2003] is used in **Chapter 3** to study the structure of the heliosphere and to obtain the plasma flow and magnetic fields that are again used in a later chapter. The set of magneto-hydrodynamic equations are given, along with the numerical solver and boundary equations. The resulting heliospheric geometry is shown and discussed, emphasizing the inability to describe such a system analytically.

Chapter 4 introduces stochastic differential equations (SDEs) and how they are applied to model CR transport. All aspects of this newly developed numerical modulation model are discussed, including benchmarks with contemporary modulation models.

In **Chapter 5**, the SDE modulation model is applied to the study of propagation times and energy losses of galactic cosmic rays in the heliosphere. Additional benchmarks of the modulation model are presented, after which both these quantities are calculated for galactic protons and electrons in different drift cycles.

Jovian electrons are included in the modulation model in **Chapter 6**. The implementation of this second CR electron species is discussed, whereafter general results of galactic and Jovian electron intensities in the inner heliosphere are presented. Then, the propagation times of

Jovian electrons are calculated and compared to observations in an effort to determine the contribution of Jovian electrons to the total electron energy spectrum measured at Earth.

In **Chapter 7**, the SDE modulation model is refined to include the waviness of the heliospheric current sheet and the subsequent drift effects. The methodology employed to do so is described, along with selected benchmark studies. Thereafter, the model is used to simulate the characteristic drift effects as observed at Earth. The propagation times of galactic protons are calculated as a function of tilt angle to investigate the effectiveness of neutral sheet drift, whereupon the proton and anti-proton energy spectra are calculated at Earth and compared to recent PAMELA observations.

In **Chapter 8**, a hybrid model for CR modulation is discussed, where the modulation model is coupled to a magneto-hydrodynamically simulated heliospheric environment. The coupling between the two models is described and general results presented. The model is then applied to the study of CR modulation beyond the heliopause.

Extracts from this thesis were published in the following peer-reviewed journals:

1. Strauss, R.D., Potgieter, M.S., Ferreira, S.E.S. *Cosmic ray modulation beyond the heliopause: A hybrid modelling approach*. The Astrophysical Journal, 765, L18, 2013.
2. Strauss, R.D., Potgieter, M.S., Ferreira, S.E.S. *Modelling and observing Jovian electron propagation times in the inner heliosphere*. Advances in Space Research, 51, 39, 2013.
3. Strauss, R.D., Potgieter, M.S., Kopp, A., Büsching, I. *Modelling heliospheric current sheet drift in stochastic cosmic ray transport models*. Astrophysics and Space Science, 339, 223, 2012.
4. Strauss, R.D., Potgieter, M.S., Kopp, A., Büsching, I. *On the propagation times and energy losses of cosmic rays in the heliosphere*. Journal of Geophysical Research, 116, A1105, 2011.
5. Strauss, R.D., Potgieter, M.S., Büsching, I., Kopp, A. *Modelling the modulation of galactic and Jovian electrons by stochastic processes*. The Astrophysical Journal, 735, 83, 2011.