Chapter 11

Summary and conclusions

This work focussed on calculating cosmic ray intensities at Earth and along both Voyager trajectories using a 2D time-dependent modulation model. The model was improved by introducing recent theoretical advances in transport theory which leads to different time-dependencies in heliospheric transport coefficients. Also, a dynamic inner heliosheath was implemented in the model. The study focussed on time-dependent cosmic ray modulation in the outer heliosphere but selective results were also computed in the inner heliosphere. By comparing modelling results with various spacecraft observations, different conclusions were made which are summarised below.

The chapters in this thesis are divided and summarised as follows:

In Chapter 1, the reader was first given a brief introduction to the time-dependent modulation of cosmic rays in the heliosphere and a thesis overview. In Chapter 2, the necessary background to understand cosmic ray modulation in the heliosphere was given. This includes the Sun, the structure of the Sun, different observed features on the Sun, the solar activity cycle, solar wind, heliospheric magnetic field, heliospheric current sheet, boundaries of the heliosphere, galactic cosmic rays, cosmic ray modulation and different spacecraft missions relevant to this study.

In Chapter 3, an overview of the *Parker* (1965) transport equation, which contains all the major modulation processes namely convection, energy changes, diffusion and drifts was given. The diffusion tensor $\mathbf{K}$ in a heliospheric magnetic field aligned coordinate system was elaborated on. A background on heliospheric turbulence was given since the diffusion parameters depend on these turbulence quantities. This work used the parallel diffusion coefficient $K_{||}$ at Earth computed by *Teufel and Schlickeiser* (2002, 2003) using the damping model. For the rigidity dependence of $K_{||}$ the analytical approximations by these authors were assumed. For the radial dependence, a similar dependence as used by *Burger et al.* (2008); *Engelbrecht* (2008) and *Strauss* (2010) is assumed for distances inside the termination shock. At the termination shock, $K_{||}$ is decreased by the compression ratio, $s_k = 2$, and then further decreased as r^{-1} inside the inner heliosheath. The perpendicular diffusion coefficient $K_\perp$ is assumed as $K_\perp \propto K_{||}$ (*Le Roux et al.*, 1999; *Giacalone and Jokipii*, 1999; *Qin et al.*, 2002a) and also $K_{\perp\theta} > K_{\perp r}$ (with

$K_{\perp\theta}$ the perpendicular diffusion coefficient in the polar direction and $K_{\perp r}$ the perpendicular diffusion coefficient in the radial direction) to attain a more realistic latitudinal gradients for cosmic ray computations (e.g. *Ferreira*, 2002; *Manuel et al.*, 2011a,c; *Ngobeni and Potgieter*, 2011). Also, in order to reproduce the observed Ulysses cosmic ray intensity gradients an enhanced latitudinal transport, as suggested by *Burger et al.* (2000), is implemented.

Cosmic ray particles experience gradient, curvature and current sheet drift motions in the heliosphere. In the 2D time-dependent modulation model the heliospheric current sheet is simulated as proposed by *Hattingh and Burger* (1995b). This aspect was also elaborated on in Chapter 3. The drift coefficient K_A used in this work is adapted from *Burger et al.* (2000, 2008). Also, in this chapter computed steady-state example solutions of cosmic ray intensities is shown to illustrate the effect of different parameters on the distribution of cosmic rays in the heliosphere.

In Chapter 4, a brief overview on the history of different cosmic ray modulation models was given. The modified ADI numerical scheme on which the model in this work is based on was developed by *Le Roux* (1990) and *Potgieter and Le Roux* (1992). This model solves the *Parker* (1965) transport equation for two spatial coordinates, a rigidity and a time coordinate. The boundary conditions are specified with r_1, the inner heliospheric boundary assuming a reflective Sun which means that no particles can enter or leave this boundary. An outer boundary, r_b, is assumed where the heliopause spectra for the particular particle species are used as the input spectrum, f_g.

In Chapter 5, time-dependent cosmic ray modulation was discussed. The GMIR/drift and compound approach to model cosmic ray intensities over a solar cycle were also discussed. The GMIR/drift approach developed by *Le Roux and Potgieter* (1995) combined drifts and GMIRs to compute time-dependent cosmic ray modulation in the heliosphere. The compound approach developed by *Ferreira* (2002) and *Ferreira and Potgieter* (2004) considered the time-dependent global changes in the heliospheric magnetic field and tilt angles to construct a time dependence in the transport coefficients. The time-dependence in the compound approach was constructed by comparing the modelling results with observations during different solar cycles. Using this approach the model successfully computed compatible cosmic ray intensities in the inner and outer heliosphere when compared to spacecraft observations. The compound approach also successfully reproduces latitudinal gradients in the cosmic ray intensities when compared to the observations along the Ulysses and Voyager trajectories. See also *Ndiitwani* (2005); *Magidimisha* (2011).

In Chapter 6, recent developments in the theoretical work on transport theories by *Teufel and Schlickeiser* (2002), *Teufel and Schlickeiser* (2003), *Shalchi et al.* (2004) and *Minnie et al.* (2007) were introduced to improve the compound approach. The current sheet tilt angle values, magnetic field magnitude measurements at Earth and statistical variance in the magnetic field are used as input parameters to construct a time-dependence in the transport parameters, based on the basic features of recent theoretical studies. In the model, all these time-dependent effects are transported out into the simulated heliosphere with the solar wind speed. This modified compound approach gave compatible results when compared to spacecraft observations (Voyager 1, Voyager 2, IMP 8 and Ulysses) on a global scale. This approach also compares well to the previous compound approach of *Ferreira* (2002) and *Ferreira and Potgieter* (2004) until ∼2004 at Earth but afterwards the model failed to reproduce the observations in the inner heliosphere and computed lower intensities. A thorough parameter study was conducted by testing the effects of different parameters like the heliopause position, termination shock position, compression ratio, different diffusion coefficients etc., on the computed cosmic ray intensities. It was found that the expected solar-cycle related changes in these parameters do not lead to improved compatibility with observations at Earth after ∼2004. This suggested a need to modify the assumed time-dependence in the diffusion coefficients.

In Chapter 7, the effect of the time-dependence in the magnetic field variance, δB^2, on the cosmic ray modulation was investigated. It was found that a smaller amplitude in the variance from solar minimum compared to maximum was more appropriate to reproduce the cosmic ray observations along the Voyager 1 trajectory but still not enough to reproduce the observations at Earth from ∼2004 onwards. The effect of the drift coefficient on cosmic ray modulation was also investigated and it was found that a modification to the time-dependent function, which scales drifts over a solar cycle, is not sufficient to compute compatible results after ∼2004. This suggested that the time-dependence in the parallel and perpendicular diffusion coefficients, as assumed in Chapter 6, should be modified by introducing a new approach. This led to better compatible modelling result along the Voyager 1 trajectory and at Earth even for the period after ∼2004. The result also showed that for the present polarity cycle, the cosmic ray modulation is no longer largely determined by changes in the drift coefficient but also to changes in the diffusion coefficients. This gave results which compared well with the traditional compound approach of *Ferreira* (2002) and *Ferreira and Potgieter* (2004) and the observations along Voyager 1 and at Earth on a global scale. However, for extreme solar maximum conditions the computed step-like modulation is not as pronounced as observed, indicating that some merging in the form of global interaction regions is needed.

In Chapters 8, cosmic ray intensities along the Voyager 2 trajectory were computed and then compared with the Voyager 2 observations. The study revealed that when the same modulation parameters, which resulted in compatible intensities along Voyager 1, were assumed along Voyager 2 trajectory, the model failed to reproduce observations. The study also found that any change in diffusion parameters alone could not reproduce the cosmic ray observations along Voyager 2 so that changes to the heliospheric geometry were necessary. It was found that if the heliosheath thickness was made smaller by changing the termination shock position and keeping the boundary position the same, the model still computed a solar cycle dependence with decreasing intensities after ∼2010 along the Voyager 2 trajectory whereas the observations show a gradual increase in intensities. This is because Voyager 2 at ∼91 AU in 2010 was still relatively far from the boundary with enough modulation volume between it and the boundary to give solar cycle effects. The assumed heliosheath thickness was reduced by changing the heliopause position from 119 AU to 100 AU for Voyager 2. An optimal (best fit) modelling result compatible to cosmic ray observations along Voyager 2 was computed. The computed cosmic ray intensities along both Voyagers suggest that the heliosphere is asymmetric and this could change if a different heliopause spectrum is assumed along Voyager 2.

In Chapter 9, future $E > 70$ MeV and 133-242 MeV cosmic ray proton intensities along the Voyager 1 and Voyager 2 spacecraft trajectories were predicted. The input parameters, such as the tilt angle, heliospheric magnetic field magnitude and total variance were extrapolated to predict intensities. It was found that a symmetrical heliosphere with different heliopause spectra values assumed at the boundary in both hemispheres resulted in incompatible results compared to observations, suggesting an asymmetrical heliosphere is necessary to simulate the Voyager 2 observations. The computed intensities along Voyager 1 increase with an almost constant rate since the spacecraft is relatively close to the heliopause. However, the model shows that Voyager 2 is still under the influence of temporal solar activity changes because of the large distance to the heliopause when compared to Voyager 1. Furthermore, the model predicted that along the Voyager 2 trajectory the intensities should remain generally constant for the next few years and then should start to steadily increase as in the case of present Voyager 1 observations. Also, this investigation shows that without knowing the exact location of the heliopause and the detail of the transport parameters one could not conclude anything about the heliopause spectra value at these energies.

Lastly, in Chapter 10 a dynamic inner heliosheath width was implemented in the model. The termination shock positions as proposed by *Snyman* (2007) and *Webber and Intriligator* (2011) along both the Voyager trajectories were used as additional time-dependent input parameters in the model. The study shows that implementing such a time-dependent termination shock profile alone in the model does not lead to improved compatibility with the observations but a time-dependent termination shock position along with a time-dependent heliopause position is required. The excursions of the heliopause position is found to be smaller along the Voyager 1 and Voyager 2 trajectory compared to the excursions of the termination shock positions. The study also suggests that the ratio between the heliopause distance and termination shock distance to be largely a constant (*Muller et al.*, 2006, 2009), although fluctuations are expected because of the dependence on the solar cycle. The different heliopause positions, indirectly estimated by comparing the cosmic ray modelling results to Voyager observations, are largely compatible until ∼2010 to the heliopause positions computed by multiplying the proposed termination shock positions by a constant. The ratio of the heliopause to termination shock position along the Voyager 1 trajectory was found to be ∼1.35 and along the Voyager 2 trajectory it was found to be ∼1.2 until ∼2010. The smaller ratio along Voyager 2 compared to Voyager 1 is possibly due to a heliospheric asymmetry. After 2010, the heliopause and termination shock position is found to be nearly a constant until 2012 which is different to that calculated from the proposed termination shock profiles from *Snyman* (2007) and *Webber and Intriligator* (2011) for these periods. The model predicts the heliopause and termination shock positions in 2012 to be respectively at ∼119 AU and ∼88 AU along the Voyager 1 trajectory and at ∼100 AU and ∼84 AU along the Voyager 2 trajectory.

The research presented in this thesis successfully addresses questions regarding the time-dependent modulation of cosmic rays in the outer heliosphere. Recommendations for improvements are:

- The 2D time-dependent transport model used in this study could be further improved by introducing a time-dependence in the rigidity dependence of the different transport coefficients and also by adding the merging of propagating diffusion barriers.
- This model could be coupled with MHD models to provide a more realistic plasma and magnetic field environment in which cosmic ray transport can be calculated.
- Different aspects of this study can be revisited once the Voyagers measure the heliopause spectrum and heliopause position. This will help to gain insight into the values of different transport parameters in the heliosphere, especially in the heliosheath.
- To do a study of time-dependent modulation of other cosmic ray species, such as electrons in the outer heliosphere.

Extracts from this thesis were published in peer reviewed journals and conference proceedings listed below:

- Manuel, R., Ferreira, S. E. S., Potgieter, M. S., Strauss, R. D., Engelbrecht, N. E.: *Time-dependent cosmic ray modulation*, Advances in Space Research, 47:1529-1537, 2011.
- Manuel, R., Ferreira, S. E. S., Potgieter, M. S.: *Cosmic ray modulation in the outer heliosphere: Predictions for cosmic ray intensities up to the heliopause along Voyager 1 and 2 trajectories*, Advances in Space Research, 48:874-883, 2011.
- Manuel, R., Ferreira, S. E. S., Potgieter, M. S., Strauss, R. D., Engelbrecht, N. E.: *Long-term galactic cosmic ray modulation in the heliosphere*, in Proceedings of the 32nd International Cosmic Ray Conference (Beijing), 2011.
- Manuel, R., Ferreira, S. E. S., Potgieter, M. S.: *Cosmic ray modulation along Voyager 1 and 2 trajectories*, in Proceedings of the 32nd International Cosmic Ray Conference (Beijing), 2011.
- Potgieter, M. S., Mwiinga, N., Ferreira, S. E. S., Manuel, R., Ndiitwani, D.C.: *The long-term variability of cosmic ray protons in the heliosphere: A modeling approach*, Journal of Advanced Research, in press, 2012.

Also this work were presented at the following conferences and workshops:

- July 2012: *Time-dependent cosmic ray modulation using a modified compound approach*, at 39th Scientific Committee on Space Research (COSPAR) 2012 at Mysore, India.
- July 2012: *Time-dependent cosmic ray modulation along Voyager 1 and 2 trajectories*, at 39th Scientific Committee on Space Research (COSPAR) 2012 at Mysore, India.
- September 2011: *Time-dependent cosmic ray modulation in the outer heliosphere: Model results along Voyager 1 and 2 trajectories*, at International Workshop - Cosmic Rays and the Heliospheric Plasma Environment 2011 at Bochum, Germany.
- August 2011: *Cosmic ray modulation in the outer heliosphere*, at 32nd International Cosmic Ray Conference (ICRC) 2011 at Beijing, China.
- August 2011: *Time-dependent cosmic ray modulation*, at 32nd International Cosmic Ray Conference (ICRC) 2011 at Beijing, China.
- July 2010: *Comparison of high energy galactic cosmic ray intensities between voyager 1 and 2*, at 38th Scientific Committee on Space Research (COSPAR) 2010 at Bremen, Germany.
- July 2010: *Possible signatures of a heliospheric asymmetry in cosmic ray observations at Voyager 1 and 2*, at 38th Scientific Committee on Space Research (COSPAR) 2010 at Bremen, Germany.
- March 2010: *Time-dependent cosmic ray modulation in the outer heliosphere*, at International Workshop - New Perspectives on Cosmic Rays in the Heliosphere 2010 at Parys, South Africa.
- July 2009: *The effects of solar cycle related changes in the cosmic ray diffusion coefficients on particle transport in the heliosphere*, at 31st International Cosmic Ray (ICRC) conference 2009 at Lodz, Poland.
- June 2009: *Time-dependent cosmic ray modulation in the heliosphere*, at IHY Africa/ SCINDA workshop 2009 at Livingstone, Zambia.
- December 2008: *Numerical modelling of solar cycle related variations in cosmic ray intensities in the heliosphere*, at Centre for high Performance Computing (CHPC) workshop 2008 at University of KwaZulu-Natal, Durban, South Africa.
- July 2008: *The effects of solar cycle related changes in the cosmic ray diffusion coefficients on particle transport in the heliosphere*, at South African Institute of Physics (SAIP) conference 2008 at University of Limpopo, Polokwane, South Africa.