Chapter 9

Summary and Conclusions

In this thesis, a newly developed numerical modulation model was discussed and applied to the transport of CRs in the heliosphere. The essential conclusions were presented at the end of each chapter and are only briefly repeated here.

In **Chapter 2**, CRs, their modulation and the relevant TPE that governs this process were introduced, while the numerical modulation model was discussed in **Chapter 4**. This chapter introduced SDEs and illustrated the equivalence between a set of SDEs and a corresponding Fokker-Planck equation. The set of SDEs that governs CR transport was derived, and it was shown how they are integrated numerically. Several successful benchmark studies of this modulation model were also shown. The terminology of pseudo-particles and pseudo-particle traces were introduced and it was shown that the SDE based model does satisfy Liouville's theorem.

After the relevant heliospheric background was presented in **Chapter 2**, a 3D MHD model was used in **Chapter 3** to simulate the heliospheric environment. The modelled heliospheric environment is qualitatively consistent with the results of more complex models and illustrates the basic heliospheric features. It was shown that an inclined ISM $\vec{B}$ can compress the southern heliospheric regions to produce a north-south heliospheric asymmetry. It was shown that, close to the HP, the ISM $\vec{B}$ lines are draped along the HP; a feature that may have significant implications for particle transport in this region. This chapter also illustrated the non-Parkerian nature of the HMF beyond the TS caused by non-radial solar wind flow. The output from this MHD model was later used in **Chapter 8** to simulate CR transport in the heliosheath.

Taking advantage of the SDE approach, CR propagation times, τ, and energy losses, ΔE, were calculated in **Chapter 5** for GCR protons and electrons. Additional successful benchmarks of the modulation model were also presented. The calculated values of τ and the fractional energy loss were compared to analytical approximations for a spatially 1D scenario and good agreement was found. For the 3D scenario, which included drift effects, τ was calculated for GCR electrons and protons reaching Earth and it was found both quantities generally decrease with increasing energy. This is a result of the choice of diffusion coefficients that increase with energy. It was found that τ is largest in the drift cycle where CRs reach Earth by mainly drifting along the HCS. The behaviour of ΔE generally follows that of τ, although the two quantities are not directly proportional. It was shown that, although ΔE for electrons is smaller than for protons of the same energy, ΔE is not negligible for electrons. Although the adiabatic limit is not observed in low energy electron intensities at Earth, these particles still experience significant amounts of adiabatic energy losses. This chapter also illustrates that when protons and electrons experience the same transport coefficients, they lose the same amount of rigidity.

In **Chapter 6**, Jovian electrons were included in the model. The methodology of implementing a second CR electron species into the modulation model was discussed. The time-dependent movement of Jupiter during the integration process was also included in the model; something that is hard to do in finite difference based models. It was however shown that the effect thereof on the modelled Jovian intensities is only pronounced in the outer heliosphere, i.e. $r >$ 30 AU, where Jupiter can move up to 31° during the time it takes these particles to reach a distance of 50 AU. It was shown that the model can reproduce the observed ~ 13 month electron periodicity as observed at Earth which is due to changing levels of magnetic connectivity between the two planets. The propagation time of 6 MeV Jovian electrons to Earth was calculated and compared to observed values in order to find the set of diffusion coefficients that best describes their transport. Using these diffusion coefficients, it was shown that $\sim 50\%$ of 6 MeV electrons observed at Earth could be of Jovian origin.

The waviness of the HCS was incorporated into the modulation model in **Chapter 7**. After the numerical implementation thereof was discussed, the model was applied to GCR proton modulation. It was shown that, by changing the HCS tilt angle and the HMF polarity, the model can reproduce both the ~ 11 and ~ 22 year CR cycles. By calculating the so-called exit position of the simulated pseudo-particles at the HP, it was shown where CRs, that are observed at Earth, enter the heliosphere in different drift cycles. The effectiveness of HCS drift for changing tilt angles was investigated and it was found that if $\alpha > 40^\circ$, neutral sheet drift becomes ineffective because the modulation process becomes increasingly diffusion dominated. The proton and anti-proton spectra at Earth were calculated for the present $A < 0$ HMF polarity cycle and were successfully compared to recent PAMELA observations. An upper limit for the proton to anti-proton ratio for the coming $A > 0$ drift cycle was also given.

The output from the MHD model discussed in **Chapter 3** was coupled to the SDE based modulation model in **Chapter 8** to create a hybrid modulation model. This coupling process was discussed, along with the transport coefficients derived from the MHD output. The calculated drift velocities were shown, and it was illustrated how these differ from the well-known Parkerian drift field inside the TS. After this, GCR proton intensities were calculated along the V1 and V2 trajectories for different polarity cycles. Emphasis was placed on the possibility of GCR modulation occurring beyond the HP, with the model results suggesting that, at 100 MeV, the proton intensities at the HP can be $\sim 40\%$ lower than the LIS level. Moreover, it was shown that modulation in this region might also exhibit solar cycle related changes. It was found that the level of modulation at the HP is not determined by the magnitude of the diffusion coefficients, but, due to the draping of the ISM $\vec{B}$ along the HP, rather by the ratio of parallel to perpendicular diffusion.

The SDE approach proved to be very successful in describing the heliospheric modulation of CRs. Overall, the modelled CR intensities and features are compatible with results from finite difference based numerical models, although the latter are unable to provide additional insights into the modulation process: As demonstrated in this thesis, an SDE based modulation model can provide the propagation times and energy losses of CRs, while pseudo-particle traces can graphically illustrate the modulation process. Numerically, an SDE based model is much easier to construct than a finite difference model, while being unconditionally stable, making it possible to study CR transport for a broader range of scenarios. The SDE model can also be executed in a parallel fashion to make use of large scale computational platforms and thus speed up calculations.

Avenues of further research related to this study are:

- Extending the MHD model by including additional plasma/neutral species.
- Studying CR transport in non-Parkerian HMF configurations.
- Refining the modulation model to include the anomalous CR component.
- Adapting the modulation model to also take into account the pitch-angle dependence of the transport coefficients, so that the transport of non-isotropic particle distributions may be studied [e.g. *le Roux and Webb*, 2009; *Zhang et al.*, 2009].