Chapter 6

Summary and Conclusions

This study presents a first attempt at the self-consistent application of the results yielded by a two-component turbulence transport model to the *ab initio* study of cosmic-ray modulation. This was done by solving the *Oughton et al.* [2011] turbulence transport model for typical solar minimum heliospheric conditions such that the turbulence quantities so acquired are in agreement with spacecraft observations taken in the solar ecliptic plane in general, and with *Ulysses* observations along its trajectory. These turbulence quantities were then used as inputs for observationally motivated forms for the slab and 2D turbulence power spectra, which were subsequently used as inputs for parallel and perpendicular mean free path expressions. The parallel mean free path expressions used are based on the quasi-linear theory (QLT) results of *Teufel and Schlickeiser* [2003], while the perpendicular mean free path expressions were derived from the extended non-linear guiding center theory (ENLGC) proposed by *Shalchi* [2006]. The use of these diffusion coefficients was motivated citing the results of observations, such as those reviewed by *Palmer* [1982], and numerical test particle simulations such as those performed by *Minnie et al.* [2007a]. To self-consistently incorporate into the model the reducing effects of the modelled turbulence on cosmic-ray drifts, an expression for the 2D ultrascale was derived from the expression for the chosen 2D turbulence power spectrum. This spectrum was constructed, following *Matthaeus et al.* [2007], in such a way as to drop off at the lowest wavenumbers. This behaviour, commencing at a wavenumber corresponding to what is termed in this study the 2D outerscale, is physically motivated by *Matthaeus et al.* [2007] and ensures a non-diverging expression for the 2D ultrascale. As the 2D outerscale is a key component of the 2D turbulence power spectrum, the perpendicular mean free paths derived using such a spectrum will also be sensitive to this quantity's behaviour. The 2D ultrascale so acquired is then used in expressions for the reduced drift coefficient proposed by *Burger and Visser* [2010], using again the results of the turbulence transport model to describe the relevant basic turbulence quantities. The drift and diffusion coefficients so acquired were then used in the three-dimensional, steady-state numerical cosmic-ray modulation code of *Hattingh* [1998].

The two-component turbulence transport model as solved in this study was found to produce results in fair to good agreement with spacecraft observations of turbulence quantities throughout the heliosphere. In a novel approach to data comparison, reasonable agreement with turbulence observations along the trajectory of *Ulysses* was also found.

The parallel mean free path expressions, for protons/antiprotons and electrons/positrons, were shown to be extremely sensitive to the behaviour of the slab variances and correlation scales acquired from the *Oughton et al.* [2011] model, exhibiting complicated spatial dependences unlike any considered in previous modulation studies. These mean free path expressions were found to be considerably above the *Palmer* [1982] consensus range values, but in qualitative agreement with the findings of, *e.g.*, *Dröge* [2000] and *Erdös and Balogh* [2005]. Parallel mean free path expressions derived for the random sweeping and the damping models for dynamical turbulence for electrons/positrons were found to be extremely sensitive to choices of parameters pertaining to the dissipation range of the slab turbulence power spectrum, such as the *Leamon et al.* [2000] models for the dissipation range breakpoint wavenumber.

Both the perpendicular mean free path expressions, and the drift reduction terms, depend on the 2D outerscale. As currently no models, or spacecraft observations, exist for this quantity, simple *ad hoc* forms for it were chosen to study its effect on the perpendicular mean free paths and drift coefficients. This effect was found to be considerable, for both quantities concerned. A larger 2D outerscale led to larger perpendicular mean free paths, and *vice versa*. Interestingly enough, various radial dependences chosen for the 2D outerscale had very little effect on the perpendicular mean free paths below approximately 2 GV. For the drift coefficient, increasing the 2D outerscale led to a significant reduction, with forms yielding smaller 2D outerscales leading to drift coefficients closer to the weak scattering case. Here, as for the case of the parallel mean free path, use of inputs from the turbulence transport model led to complicated spatial dependences for both the perpendicular mean free path expressions and drift coefficients. All the perpendicular mean free path expressions were found to remain considerably above the *Palmer* [1982] consensus range values at Earth. When the ratios of the parallel to perpendicular mean free paths were considered, however, they were found to be within the range expected of the *Palmer* [1982] consensus values for all forms of the 2D outerscale considered, but varied considerably throughout the heliosphere. The fact that the ratio of the perpendicular to parallel mean free path may vary throughout the heliosphere is usually not taken into account in most cosmic-ray modulation studies.

The application of the above results in the computation of galactic proton intensities led to some thought-provoking results. The effects of various forms for the 2D outerscale on computed proton intensities were first considered, and were found to be very significant. This was not wholly surprising, as this quantity essentially governs both the amount of drift experienced by cosmic-rays, and its perpendicular diffusion coefficient. So much so, that it was possible to find a form for the 2D outerscale which resulted in computed galactic proton intensities in fair to good agreement with multiple sets of spacecraft observations taken at various locations in the heliosphere. A choice of a larger outerscale would lead to a greater reduction of drift effects, with the largest outerscales resulting in computed intensities closely resembling those acquired when drift effects are completely ignored. The forms chosen for the 2D outerscale leading to the smallest values of this quantity resulted in computed intensities in fair agreement with solar minimum cosmic-ray spacecraft observations. A best fit form for the 2D outerscale was chosen, which results in computed galactic proton intensities in reasonably good agreement with multiple sets of spacecraft observations [*e.g. McDonald et al.*, 1992; *Heber et al.*, 1996; *Webber and Lockwood*, 2004; *Shikaze et al.*, 2007]. This agreement is not, however, perfect. Agreement of computed results with spacecraft observations at large radial distances is arguably poor, with intensities computed for the best fit 2D outerscale overshooting observations in the outer heliosphere. This, however, is not surprising given the omission of the effects of the heliosheath in the cosmic-ray modulation code used. Some modulation has been found to occur in this region [see, *e.g.*, *Caballero-Lopez et al.*, 2004b; *Webber*, 2006; *Caballero-Lopez et al.*, 2010; *Burlaga et al.*, 2011], and as this is not taken into account in this study, computed intensities at large radial distances are expected to be larger than spacecraft observations.

The sensitivity of computed cosmic-ray intensities to essentially one free parameter harkens in a sense to the force-field approach to the solution of the Parker transport equation, dependent as it is on the modulation parameter alone. The key difference in these approaches, however, is the fact that the approach employed here is strongly motivated by the basic theoretical considerations behind the self-consistent application of the 2D turbulence power spectrum here employed, and as such, multiple spacecraft datasets can be 'fit' using a single form for the 2D outerscale. This is simply not possible with the force-field approach.

Another interesting result of the *ab initio* approach to cosmic ray modulation described in this study, is that galactic proton latitude gradients computed assuming a pure Parker heliospheric magnetic field, and axisymmetric perpendicular diffusion, are in good agreement with *Ulysses* observations reported by *Heber et al.* [1996] during $A > 0$. Previous attempts to achieve this assumed either non-axisymmetric perpendicular diffusion [*e.g. Burger et al.*, 2000] or some kind of *Fisk* [1996]-type heliospheric magnetic field model. Latitude gradients computed for the $A < 0$ polarity cycle were found consistently to be too large when compared with the single data point for this magnetic polarity presented by *de Simone et al.* [2011]. This shortcoming may be resolved in future by the use of a turbulence-reduced drift coefficient derived more rigourously than the construction from numerical simulations of *Burger and Visser* [2010]. The fact, however, that an *ab initio* approach, based on the results of a two-component turbulence transport model, can lead to latitude gradients that have magnitudes in reasonable agreement with spacecraft observations, is very encouraging. In the light of this last result the effect using a Fisk-type field, namely a Schwadron-Parker hybrid field proposed by *Hitge and Burger* [2010] and reduced along the lines argued by *Sternal et al.* [2011], on galactic proton intensities was considered next. In terms of computed intensities at 1 AU and latitude gradients, the effects of such an heliospheric magnetic field model were found to be quite small. When computed relative amplitudes of recurrent cosmic-ray intensity variations were considered, results acquired using the hybrid field were generally larger than those computed using a Parker field, and in qualitative agreement with the findings of *Richardson et al.* [1999], being larger for $A > 0$ than for $A < 0$, but only at low rigidities. At higher rigidities, results for $A < 0$ are dominated by interaction with the wavy current sheet. Relative amplitudes computed using the hybrid field, when considered as functions of the corresponding latitude gradients, agree qualitatively with the results presented by *Zhang* [1997] during $A > 0$, but only at small rigidities for $A < 0$. The magnitude of these computed relative amplitudes remains far below the actual values for this quantity reported by *Zhang* [1997]. This, coupled with the fact that the *ab initio* model cannot reproduce the expected relative amplitudes when a purely Parker field is assumed, implies that a Fisk-type field may still be reasonable explanation for the observed cosmic-ray variations at high latitudes, but that such a field needs be modelled to have a stronger 'Fisk-effect' than proposed by the *Sternal et al.* [2011] study.

Computed galactic electron intensities were found to be extremely sensitive to even moderate changes in turbulence quantities pertaining to the dissipation range of the slab turbulence power spectrum. At higher energies, computed galactic electron differential intensities displayed no sensitivity to dissipation range parameters, and were found to be in fair agreement with spacecraft observations. Computed galactic electron latitude gradients were found to fall within the uncertainty of the single data point reported by *Heber et al.* [2008], displaying as expected a high degree of sensitivity to the choices made as to dissipation range parameters at low rigidities. An investigation into the effects the extrapolated *Leamon et al.* [2000] models for the dissipation range spectral breakpoint wavenumber would have on computed galactic electron intensities, revealed that only one of these models, the fit through origin proton gyrofrequency model, led to intensities at lower energies in qualitative agreement with observations. The other models resulted in galactic electron spectra that displayed a clear charge-sign dependence even unto the lowest energies, a clearly unphysical result. One model was already eliminated because it does not yield a finite dissipation range above the solar poles. Varying the dissipation range spectral index also had a significant effect on low energy electron differential intensity spectra, with the solutions computed using a small value ($p = 2.3$) for this quantity exhibiting charge sign dependences contrary to observations, while the use of a large ($p = 2.8$) value led to intensities so large as to agree with observations believed to contain a large Jovian component, such as those reported by *Moses* [1987]. The abovementioned results were obtained assuming electron parallel mean free paths derived using the random sweeping model for dynamical turbulence. Differential intensities computed assuming mean free paths derived using the damping model of dynamical turbulence displayed a clear charge-sign dependence at lower energies, regardless of what was assumed for the dissipation range spectral index. The underlying pattern in these low energy electron results is that dissipation range turbulence quantities need be chosen very specifically so as to compute realistic galactic electron intensities. More specifically, the *ab initio* model is extremely sensitive to the behaviour of the low-energy parallel mean free paths in the outer heliosphere. A dissipation range turbulence quantity that results in a too-small parallel mean free path will lead to a scenario where the effects of drift dominate the effects of diffusion in the outer heliosphere, leading to charge-sign dependent differential intensities at Earth. These results again raise the possibility that it may be possible to use cosmic-ray observations at Earth as a diagnostic from which conclusions may be drawn as to the global behaviour of some turbulence quantities in general, or at the least on the behaviour of turbulence quantities pertinent to the dissipation range of the turbulence power spectrum.

Galactic positron and antiproton intensities were also computed, again using the best fit form for the 2D outerscale, and for the positrons, a best fit set of dissipation range parameters based on the computed galactic electron results discussed above. Computed differential intensities for both species were found to be in reasonably good agreement with spacecraft observations at Earth. The positron diffusion coefficients were held to be the same as those for electrons, and the antiproton diffusion coefficients were the same as those for protons. The antiproton/proton ratio was computed, using best fit galactic proton intensities, and were found to be in agreement with spacecraft observations of this quantity. The computed positron fraction was also compared to spacecraft observations, and found to be in reasonable agreement with them at intermediate energies for both magnetic polarity cycles. The agreement of the positron fraction with observations at higher energies was less good, but this may simply be due to the fact that the local interstellar spectrum here employed does not take into account possible primary sources of these particles [*Adriani et al.*, 2009b].

To conclude then, an *ab initio* treatment of diffusion and drift, incorporating in as self-consistent a way possible the effects of turbulence as described by a two-component turbulence transport model, set in such a way as to yield results in reasonable to good agreement with spacecraft observations of turbulence quantities, can yield computed cosmic-ray intensities in reasonably good agreement with multiple sets of spacecraft observations, and for different cosmic-ray species.

Possible avenues of future research stemming from this study include:

- Applying the ab initio approach outlined in this study to the study of cosmic-ray modulation employing a stochastic solver, such as that used by *Pei et al.* [2010b], for the Parker transport equation. This will allow for the study of time-dependent effects.
- The application of the results of other scattering theories to the study of cosmic-ray modulation, such as the weakly non-linear theory proposed by *Shalchi et al.* [2004b], or the approach to the non-linear guiding center theory proposed by *Ruffolo et al.* [2012].
- Considering the effects of a time-dependent wavy neutral sheet.
- The inclusion of a Jovian electron source into an *ab initio* model.
- A detailed comparison of results acquired using turbulence transport models where turbulent driving is assumed to occur at all scales, as opposed to at approximately the correlation scale as was implicitly assumed in this study.

There is little doubt that currently the most pressing need in modulation studies is for a well-motivated theoretical expression for the drift coefficient, one that can fit direct numerical simulations. In this regard, more numerical simulations are needed to improve our knowledge of how this elusive transport coefficient depends on turbulence quantities, and perhaps on other transport coefficients.

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