Chapter 1

Introduction

Various processes influence the modulation of galactic cosmic-rays in the heliosphere. Two of these are incorporated into the diffusion tensor for cosmic-rays: diffusion, parallel and perpendicular to the background magnetic field, and gradient and curvature drift. Many scattering theories, describing the interaction of charged particles with the turbulent heliospheric magnetic field, are available [see, *e.g.*, *Shalchi*, 2009], from which expressions for diffusion coefficients can be derived. Differentiating between these theories as to which most accurately describes cosmic-ray diffusion is difficult, but due consideration of observations [see, *e.g.*, *Palmer*, 1982] and the many numerical simulations of diffusion coefficients [see, *e.g.*, *Minnie et al.*, 2007a] make an educated decision as to the applicability of the results yielded by a particular scattering theory possible. These theories, however, require as a key input some form of turbulence power spectrum, which in turn depends on the nature of the turbulence in the heliosphere. Cosmic-ray drifts have also been shown, by means of numerical simulations [see, e.g., *Minnie et al.*, 2007b], to be reduced in the presence of turbulence. Various ways have been proposed [see, *e.g.*, *Bieber and Matthaeus*, 1997; *Burger and Visser*, 2010] to model this phenomenon, and these methods all depend on some knowledge of the behaviour of turbulence throughout the heliosphere. This behaviour is relatively well understood at 1 AU [see, *e.g.*, *Bruno and Carbone*, 2005; *Matthaeus and Velli*, 2011], but considerably less so elsewhere in the heliosphere. Herein lies the difficulty in any *ab initio* approach to the study of cosmic-ray (CR) modulation: the need to self-consistently model various turbulence quantities, so as to be in agreement with extant spacecraft observations of these quantities, which would allow one to model the behaviour of turbulence power spectra throughout the entire heliosphere. With the development of turbulence transport models of ever increasing refinement [see, *e.g.*, *Breech et al.*, 2008; *Oughton et al.*, 2011; *Zank et al.*, 2012] to describe the spatial evolution of basic turbulence quantities, this endeavour has finally become possible.

This study aims to provide an outline of the process involved in applying the results of a two-component turbulence transport model derived by *Oughton et al.* [2011], by means of chosen forms for turbulence power spectra, to the study of CR modulation in as self-consistent a way possible. A two-component turbulence transport model has not before been applied to any study of cosmic-ray modulation.

The next chapter commences with a discussion and review of theoretical and observational aspects of heliospheric magnetohydrodynamic (MHD) turbulence, as applicable to the study of cosmic-ray modulation. Forms for the slab and 2D turbulence power spectra to be used in the rest of this study are chosen and motivated on the basis of the abovementioned theory and spacecraft observations. The 2D power spectrum is chosen following *Matthaeus et al.* [2007] so that it displays a drop-off at the smallest wavenumbers, commencing at a lengthscale referred to here as the 2D outerscale. This form allows for the self-consistent derivation, following the approach outlined by *Matthaeus et al.* [2007], of an expression for the 2D ultrascale required in models such as that of *Burger and Visser* [2010] for the reduction of drift by turbulence.

The subject of the third chapter is the *Oughton et al.* [2011] two-component turbulence transport model used to model the various basic turbulence quantities that are required as inputs for the spectral forms chosen in the previous chapter. A description of the approach taken in solving this model is given. Boundary values are chosen, such that the model yields results in agreement with extant turbulence datasets throughout the heliosphere. For solutions to the model beyond the solar ecliptic plane, boundary values are chosen so as to attempt agreement with observations taken by *Ulysses* along its trajectory, an approach unique to this study. The effects of a Schwadron-Parker hybrid heliospheric magnetic field [see *Hitge and Burger*, 2010; *Sternal et al.*, 2011] on model solutions are also compared with those acquired assuming a *Parker* [1958] field. This chapter closes with a characterization of model results throughout the heliosphere in general, and along *Ulysses'* trajectory in particular.

Diffusion and drift coefficients are the topic of the fourth chapter. Motivated by a brief review as to observations and simulations of parallel and perpendicular mean free paths, choices are made as to which scattering theories are to be used as the basis of the diffusion coefficients to be employed in this study. Parallel diffusion coefficients for protons/antiprotons and electrons/positrons, based on the quasi-linear theory (QLT) results of *Teufel and Schlickeiser* [2003], are discussed and characterized throughout the heliosphere, using the results yielded by the turbulence transport model as inputs for basic turbulence quantities. A perpendicular mean free path expression is derived from the extended non-linear guiding center theory (ENLGC) proposed by *Shalchi* [2006], using the 2D turbulence power spectrum discussed in the second chapter. This spectrum, as mentioned above, is a function of the 2D outerscale, a quantity for which no models or observations exist. Therefore simple, *ad hoc* forms are chosen for it, in the light of which the perpendicular mean free path expression will be characterized, again using inputs yielded by the turbulence transport model. The final sections of this chapter concern themselves with cosmic-ray drifts. Very brief reviews on this process, the implementation of its effects in the presence of a wavy current sheet, and the results of numerical simulations of the drift coefficient, will be given. The turbulence-reduced drift coefficients proposed by *Burger and Visser* [2010] and used in this study are subsequently introduced. These depend on the 2D ultrascale, which in turn is a function of the 2D outerscale. Therefore both the ultrascale and turbulence-reduced drift coefficients will, like the perpendicular mean free path expressions, be characterized throughout the heliosphere with the abovementioned *ad hoc* forms for the 2D outerscale, again utilizing the results of the turbulence transport model where necessary.

Chapter 5 applies the *ab initio* diffusion tensor constructed in the previous chapters to the study of the modulation of galactic protons, electrons, antiprotons, and positrons. This is done using the three-dimensional steady state cosmic-ray modulation code of *Hattingh* [1998], also employed by, *e.g.*, *Burger et al.* [2008]. The effects of the various forms chosen for the 2D outerscale in the previous chapter on computed galactic proton intensities are discussed and compared with several sets of spacecraft observations throughout the heliosphere. On the basis of this comparison, a 'best fit' form for the 2D outerscale is chosen, and subsequently used in all model computations. The effect of a Fisk-type heliospheric magnetic field model on computed galactic proton intensities is also considered. The *ab initio* approach is then applied to the study of antiproton modulation, and computed intensities and antiproton/proton ratios are compared with various spacecraft observations of these quantities. Galactic electron modulation is considered next. The effects of the various *Leamon et al.* [2000] models for the dissipation range breakpoint wavenumber, changes in the dissipation range spectral index within the range of spacecraft observations reported by *Smith et al.* [2006], and choice of model for dynamical turbulence employed in the derivation of the electron parallel mean free paths have on computed galactic electron intensities, will be discussed in detail, and comparisons of computed results with multiple spacecraft observations will be made. This chapter closes with a discussion of computed positron intensities, and positron fractions, with comparisons to observations made by spacecraft at 1 AU of these quantities.

A summary of the main results presented here, as well as the conclusions drawn and possible avenues of future research, is presented in the final chapter.

Selected results pertaining to this study have been presented at the 31st International Cosmic Ray Conference (2009), the 38th COSPAR conference (2010), and the 32nd International Cosmic Ray Conference (2011).