

Chapter 2

The Heliosphere, Cosmic Rays and the Heliospheric Transport of Cosmic Rays

2.1 Introduction

This chapter introduces the reader to the basics of the heliosphere, cosmic rays (CRs) and the transport of CRs inside the heliosphere. The following chapters will use the concepts and terminology introduced here and expand on the subject matter as it is applied and refined.

2.2 Formation of the Heliosphere

The heliosphere is formed as a result of the interaction between the solar and interstellar plasmas and can be defined as the local region of interstellar space influenced by the Sun. Because the Sun is the main driver of the heliosphere, the global structure thereof is heavily influenced by the Sun's temporal variations (discussed again later in this chapter), most notable the ~ 11 year solar activity cycle. To illustrate the Sun's cyclic behaviour, Fig. 2.1 shows the yearly averaged sunspot number (a number related to the amount of dark, irregularly shaped spots visible on the solar surface; also an indication of the level of solar activity) as a function of time. The Sun goes through a period of intense solar activity characterized by large sunspot numbers, referred to as solar maximum conditions, every ~ 11 years. The heliosphere is therefore far from a static structure, but inherently dynamic in nature. See *Scherer et al.* [2000] for a review of the heliosphere.

In order to remain in equilibrium, the solar atmosphere must continually expand into interplanetary space, forming the solar wind [e.g. *Parker*, 1958; *Choudhuri*, 1998]. The solar wind is observed at Earth as a radially outwards moving plasma with a proton speed of $\sim 400 - 800$ km.s⁻¹ and is supersonic (see also the next chapter). The solar wind is not always uniform over all solar latitudes, but its speed is influenced close to the Sun by the solar magnetic field, which during solar minimum conditions, develops large polar coronal holes at high latitudes that promote the outflow of solar plasma. Fig. 2.2 shows solar wind observations by the

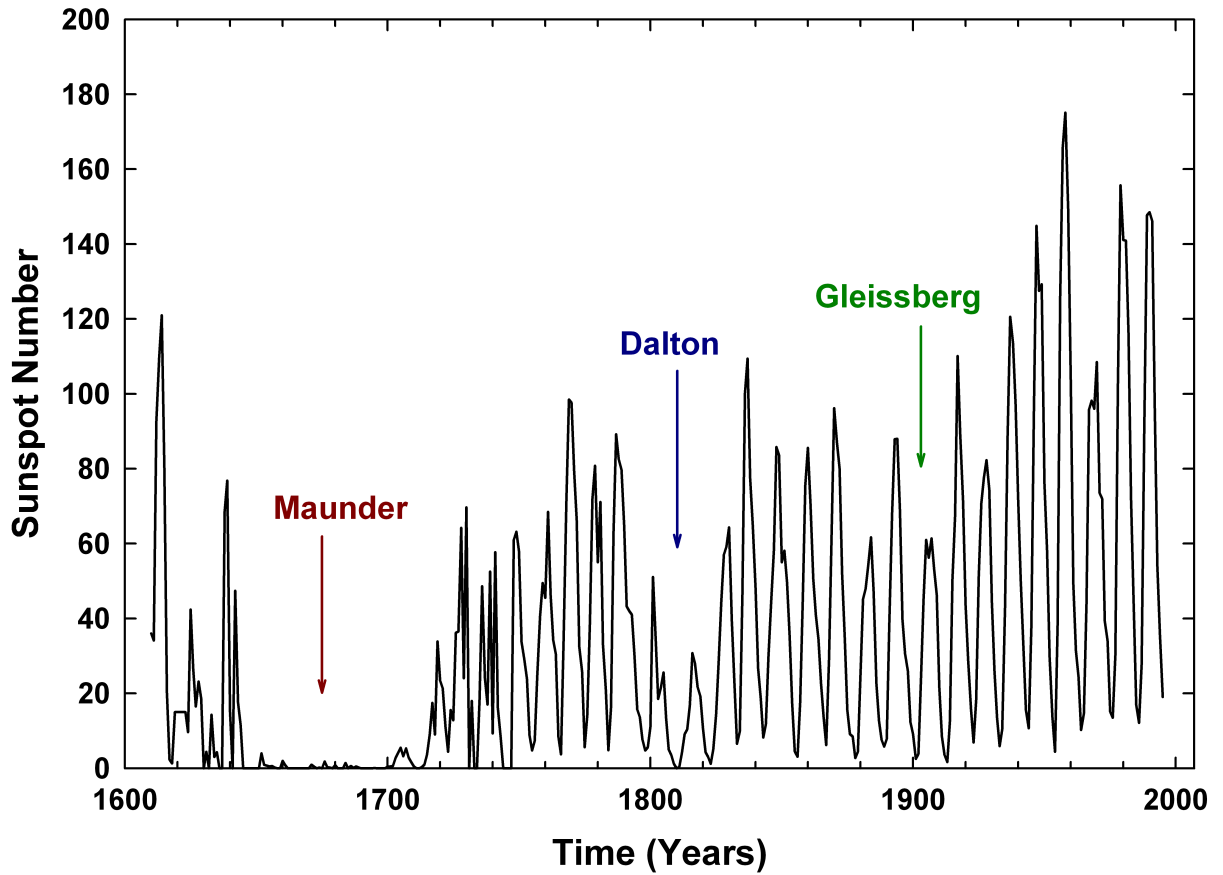


Figure 2.1: The yearly averaged sunspot number as a function of time, with several so-called *grand minima* (i.e. extended periods of low solar activity) indicated. The data is taken from the Solar Influences Data Analysis Center (<http://sidc.be>).

Ulysses spacecraft (the green lines showing proton speed and the broken black lines density) as a function of latitude during times of minimum (top panel) and maximum (bottom panel) solar activity. During solar minimum conditions at high latitudes, the presence of the coronal holes result in fast solar wind streams with speeds decreasing again near the equatorial regions [Phillips *et al.*, 1995]. During solar maximum conditions, the coronal holes are smaller and more or less uniformly distributed in the corona, so that this latitude dependence disappears. For details, see e.g. Marsden [1995] and Balogh *et al.* [2001].

Due to the motion of the Sun through interstellar space, the interstellar medium (in the rest frame of the Sun) forms an interstellar wind that interacts with the solar wind to create an asymmetrical heliospheric geometry. This is illustrated in Fig. 2.3, which shows the modelled proton density in the meridional plane of the heliosphere. Interstellar flow is directed towards the left with the Sun fixed at the origin. Because of interstellar inflow, the heliosphere develops a very distinctive highly asymmetrical shape, being heavily compressed in the nose region while being elongated in the tail region. The different structures that comprise the heliosphere are the terminations shock (TS, where the supersonic solar wind drops to subsonic speeds), the heliopause (HP, which separates the solar and interstellar plasmas) and the bow-shock (BS,

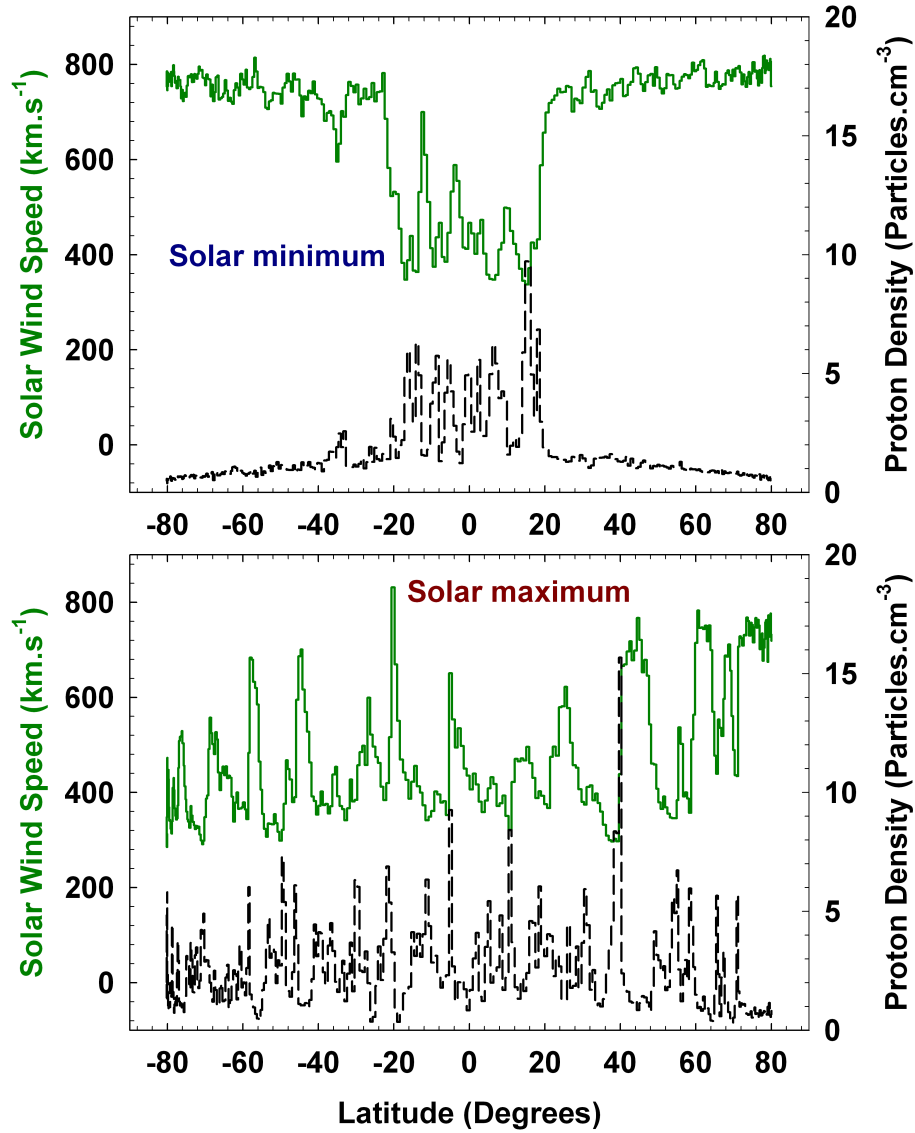


Figure 2.2: Ulysses observations of the solar wind proton speed (green lines) and density (broken black lines) as a function of solar latitude for times of solar minimum (top panel) and maximum (bottom panel) activity. The data is taken from the NSSDC COHOWeb: <http://cohoweb/gsfsc.nasa.gov>.

where the interstellar medium flow speed drops to subsonic values). The processes forming the heliosphere, as well as the different structures that constitute the heliosphere, are discussed in detail in the next chapter.

2.3 The Heliospheric Magnetic Field

Away from the Sun, the solar wind kinetic energy dominates the magnetic energy contained in the solar wind, so that the Sun's magnetic field is embedded in the solar wind, and consequently convected into interplanetary space, forming the heliospheric magnetic field (HMF).

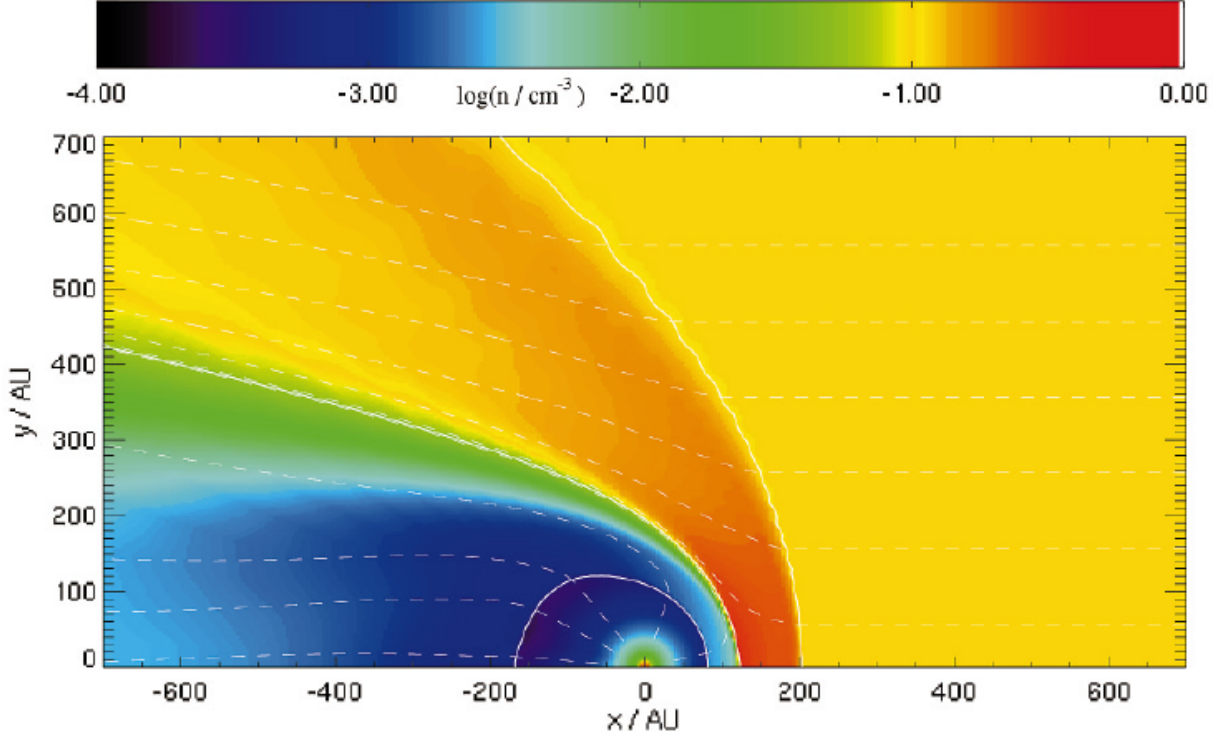


Figure 2.3: The modelled heliospheric environment in terms of proton density in the meridional plane of the heliosphere. The white dashed lines indicate plasma flow. The figure is taken from *Fahr et al.* [2000]. Along the positive x -axis, the TS (75 AU), the HP (125 AU) and the BS (200 AU) are clearly visible.

The first HMF model was developed by *Parker* [1958] and is referred to as the Parker HMF. In this model the HMF is directed radially outwards in the rest frame of the Sun, while the Sun's rotation causes these field lines to form Archimedean spirals that extend into interplanetary space. The Parker HMF can be written as

$$\vec{B} = AB_0 \left[\frac{r_0}{r} \right]^2 (\mathbf{e}_r - \gamma \mathbf{e}_\phi), \quad (2.1)$$

with B_0 a normalization value, usually related to the HMF magnitude as observed at Earth, B_e , so that

$$B_0 = B_e \left[1 + (\Omega r_0 / V_{sw})^2 \right]^{-1/2}. \quad (2.2)$$

The HMF spiral angle Ψ , defined as the angle between the HMF and the radial direction, is incorporated in the function

$$\gamma \equiv \tan \Psi = \frac{\Omega r \sin \theta}{V_{sw}}, \quad (2.3)$$

with Ω being the solar rotation rate, V_{sw} the solar wind speed and (r, θ, ϕ) referring to the spherical coordinate system used here and $(\mathbf{e}_r, \mathbf{e}_\theta, \mathbf{e}_\phi)$ the corresponding unit vectors. The

HMF polarity is determined by

$$A = \pm H(\theta - \theta'), \quad (2.4)$$

with

$$H(\theta - \theta') = \begin{cases} 1 & : \theta < \theta' \\ 0 & : \theta = \theta' \\ -1 & : \theta > \theta', \end{cases} \quad (2.5)$$

a step function, θ' the angular extent of the heliospheric current sheet (HCS, discussed in the next section) with ± 1 referring to the different HMF polarity cycles as discussed in section 2.5.

Several modifications to the Parker HMF have been proposed to incorporate more complex solar dynamics [e.g. *Smith and Bieber, 1991; Fisk, 1996*]. For the purposes of this thesis however, an unmodified Parker HMF is used in the supersonic solar wind regions.

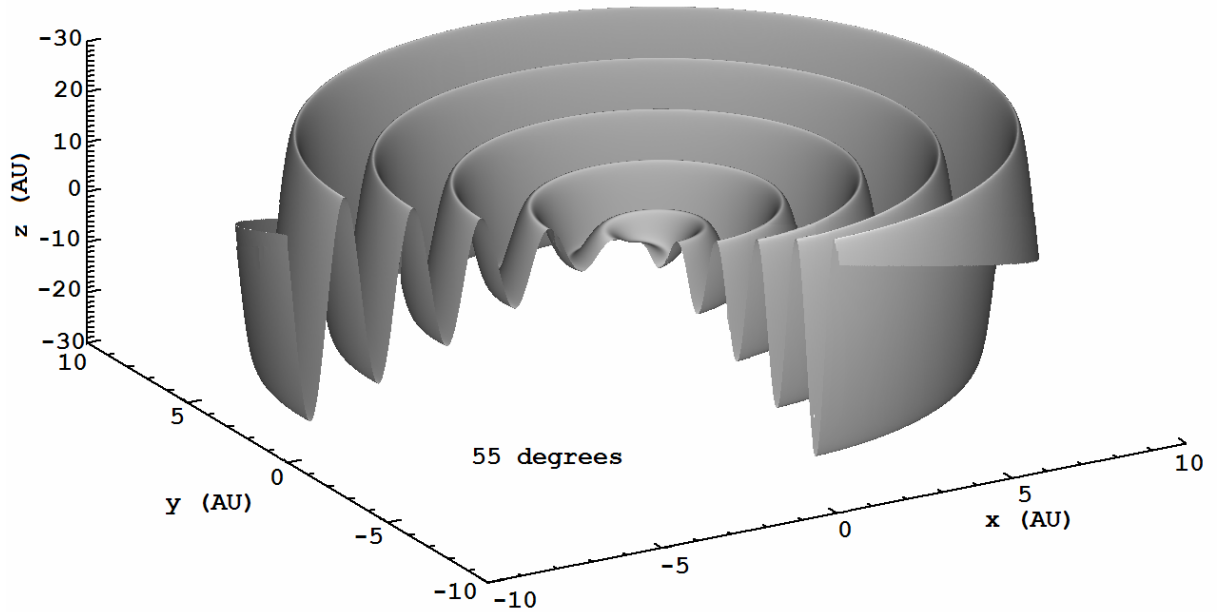


Figure 2.4: The HCS as the shaded surface for the first 10 AU from the Sun, located at the origin, using $\alpha = 55^\circ$. The negative quadrant of the surface is removed to make the HCS structure clearer.

2.4 The Heliospheric Current Sheet

The HCS is the boundary separating regions of opposite polarity of the HMF [e.g. *Smith, 2001*]. If the magnetic and rotational axes of the Sun would be aligned, the HCS would form as a flat sheet located at $\theta' = \pi/2$, thus lying in the equatorial plane. These axes are however misaligned

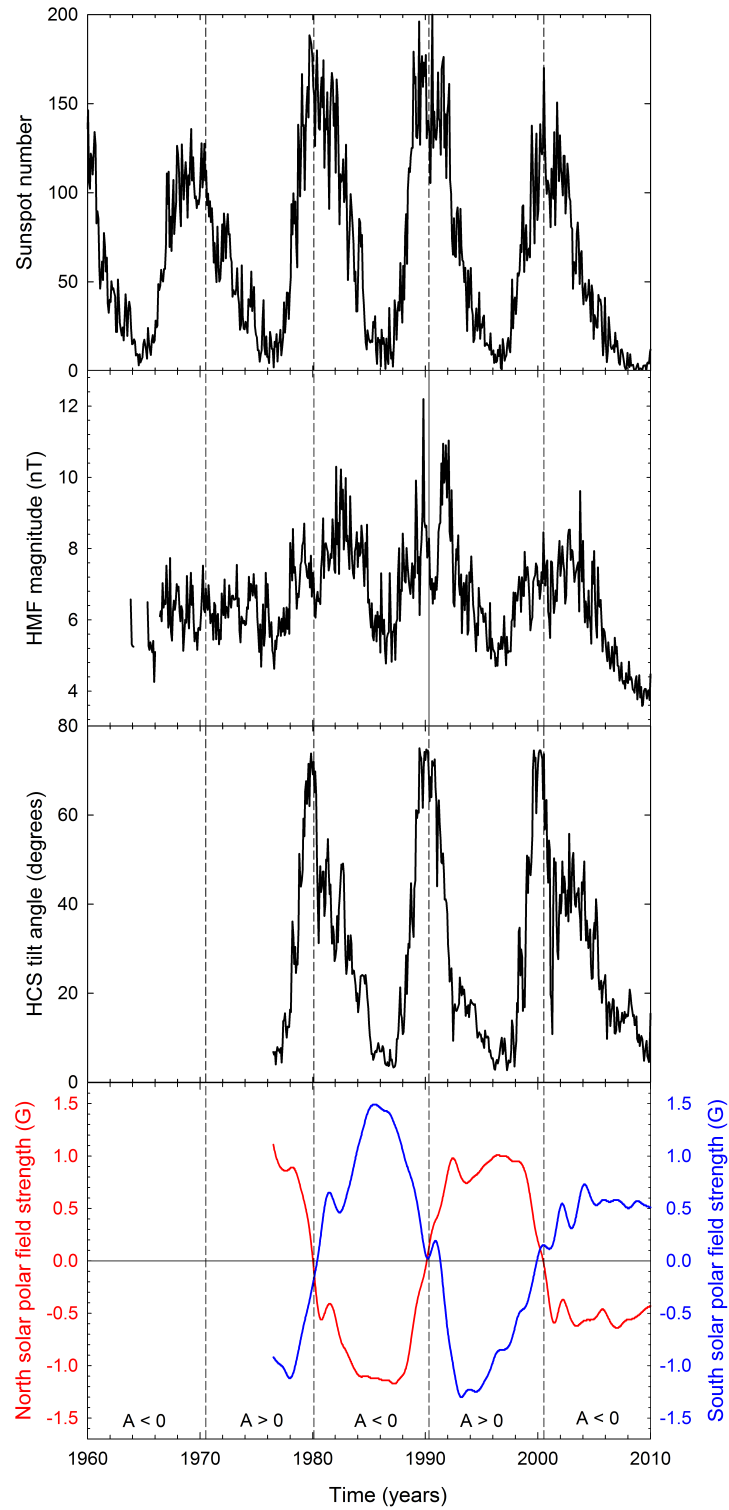


Figure 2.5: Temporal variations of the sunspot number, the MHF magnitude (as observed at Earth), the HCS tilt angle and the northern and southern solar polar magnetic field strength. The vertical lines indicate times of solar maximum activity when the HMF switches polarity. The HMF data is taken from the NSSDC COHOWeb (<http://cohweb/gsfsc.nasa.gov>), while the HCS and solar magnetic field data are from the Wilcox Solar Observatory (<http://wso.stanford.edu>).

by the so-called tilt angle, $\alpha \in [0, \pi/2]$, so that the latitudinal extent of the HCS is rather given by

$$\theta' = \frac{\pi}{2} + \sin^{-1} \left\{ \sin \alpha \sin \left(\phi - \phi_0 + \frac{\Omega r}{V_{sw}} \right) \right\}, \quad (2.6)$$

where ϕ_0 is an arbitrary azimuthal phase constant [e.g. *Jokipii and Thomas, 1981*]. Moreover, α is also time dependent, as discussed in Section 2.5. The HCS is shown in Fig. 2.4 as a shaded surface for the first 10 AU from the Sun using $\alpha = 55^\circ$. Note that the negative quadrant is removed from the figure for clarity and that z gives the direction above the equatorial plane. When $\alpha \neq 0$, the HCS thus exhibits a wavy structure, also referred to as a *ballerina skirt*.

2.5 Solar Activity

As mentioned in Section 2.2, the heliosphere is a dynamic system driven by the ~ 11 year solar activity cycle. Fig. 2.5 illustrates this behaviour by showing the temporal evolution of the HMF magnitude as measured at Earth and the HCS tilt angle as compared to the sunspot numbers shown previously. During solar maximum periods (indicated by the vertical lines), both the HMF magnitude and the HCS tilt angle become larger and obtain their maximum values, while decreasing again with decreasing solar activity. For modulation studies, α is also the most often used solar proxy.

The ~ 22 year magnetic cycle is illustrated in the bottom panel of the figure which shows the northern and southern solar polar magnetic field strength. The polarity of the HMF switches every ~ 11 years during solar maximum conditions, leading to this ~ 22 year cycle. Times when the northern HMF points away from the Sun (e.g. $\sim 1970 - 1980$), are referred to as $A > 0$ polarity cycles (thereby also defining the sign of the quantity A in Eq. 2.4), while opposite polarity cycles are referred to as $A < 0$ polarity cycles, as indicated in the figure.

See e.g. *Marsden [2001]* and *Balogh et al. [2008]* and *Hathaway [2010]* for more details concerning the heliospheric solar activity cycles.

2.6 Cosmic Rays

For the purposes of this thesis, CRs are defined broadly as non-thermal charged particles that are accelerated both inside and outside of the heliosphere. CRs are generally classified according to their origin and the CR species pertinent to this study are briefly discussed below. In this thesis, the focus is on modelling the modulation of galactic CRs, more specifically, the proton, electron and anti-proton populations, as well as Jovian electrons. For a review on CRs, see e.g. *Heber and Potgieter [2006]* and *Potgieter [2008b]*.

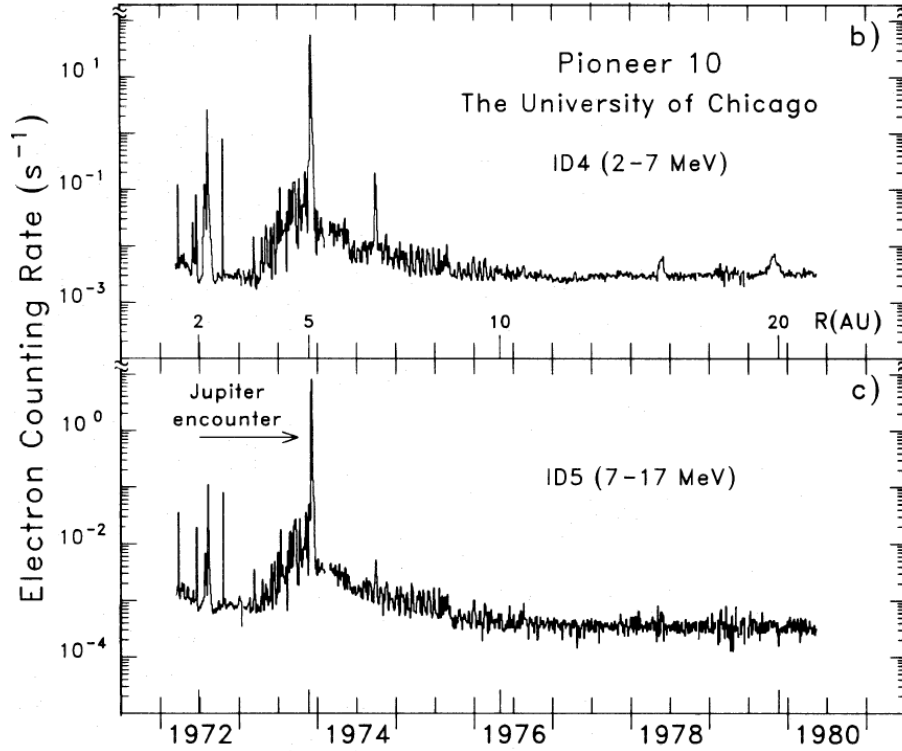


Figure 2.6: The electron counting rate measured by the Pioneer 10 spacecraft as a function of radial distance and time for two energy channels. The figure is taken from *Eraker* [1982].

2.6.1 Galactic Cosmic Rays

Galactic CRs (GCRs) are highly energetic and fully ionized charged particles that originate outside of the heliosphere with energies of up to 10^{12} GeV [e.g. *Hillas*, 2006]. Below ~ 100 GeV, the heliosphere can modulate the GCRs so that their *true* intensities outside the heliosphere (i.e. well beyond the HP) cannot be measured directly at Earth. As the following chapters will show, this is an energy-dependent process, where the amount of modulation generally increases with decreasing energy. The most likely GCR accelerators are believed to be supernovae throughout the galaxy [e.g. *Moskalenko et al.*, 2002], although other astrophysical systems, e.g. pulsars, are known to accelerate GCRs [e.g. *Büsching and Potgieter*, 2008].

In order to model the heliospheric modulation of GCRs, i.e. their transport from the HP to Earth, the intensity of the different GCR species directly at the HP must be known and prescribed as a boundary condition in any modulation model. To achieve this, results from galactic propagation models that describe the transport of GCRs within the galaxy [e.g. *Moskalenko et al.*, 2002; *Strong et al.*, 2011], are used to estimate the intensity of the GCRs at the HP; simply assumed to be the local interstellar spectrum (LIS). This LIS is then modulated as the GCRs propagate towards the inner heliosphere.

The transport of GCRs is revisited in Chapters 5, 7 and 8.

2.6.2 Jovian Electrons

During the Pioneer 10 spacecraft encounter with the Jovian magnetosphere, Jupiter was proven to be a strong source of low energy ($E < 100$ MeV) electrons. In fact, Jovian electrons are the dominant electron population at these energies in the inner heliosphere [Ferreira, 2002; Heber and Potgieter, 2006; Potgieter and Nndanganeni, 2013]. Fig. 2.6 shows the Pioneer 10 electron counting rate observations in terms of radial distance and time [Eraker, 1982]. It is clear that the maximum intensity of CR electrons at these energies occur at Jupiter's position (i.e. at a radial distance of 5.2 AU).

The transport of Jovian electrons is discussed further in Chapter 6.

2.6.3 Other Species

Other CR species that will not be investigated in this thesis is the energetic particle component [see e.g. Dröge, 2000] that originates from the Sun, as well as the anomalous CR component, which is a mostly singly ionized CR species that forms when neutral interstellar material gets ionized in the heliosphere and is accelerated in the outer heliosphere. For a recent review regarding anomalous CRs, see e.g. Giacalone *et al.* [2012].

2.7 The Cosmic Ray Transport Equation

The transport of CRs inside the heliosphere is governed by the *Parker* [1965] transport equation (TPE),

$$\frac{\partial f}{\partial t} = - \left(\vec{V}_{sw} + \vec{v}_d \right) \cdot \nabla f + \nabla \cdot (\mathbf{K} \cdot \nabla f) + \frac{1}{3} \left(\nabla \cdot \vec{V}_{sw} \right) \frac{\partial f}{\partial \ln P} \quad (2.7)$$

given in terms of the gyro- and isotropic CR distribution function $f(r, \theta, \phi, P, t)$ (in spherical spatial coordinates) which is related to the CR differential intensity by $j(r, \theta, \phi, P, t) = P^2 f(r, \theta, \phi, P, t)$, where P is particle rigidity. A re-derivation of the TPE was given by Webb and Gleeson [1979], while the TPE in its present form can also be derived by averaging the Fokker-Planck equation over pitch angle [e.g. Schlickeiser, 2002; Stawicki, 2003]. The processes included in the TPE and described by the associated terms, are from left to right: Temporal changes, convection due to the embedded HMF being convected with the solar wind velocity $\vec{V}_{sw}$, particle drifts, diffusion and adiabatic energy changes due to an expansion or compression of the background plasma (see also Chapter 3). Additional processes, e.g. momentum diffusion [Fermi II acceleration; see e.g. Ferreira *et al.*, 2007a], can also be included into the TPE by including the corresponding terms, while diffusive shock (Fermi I) acceleration is already included in the adiabatic term in its present form [e.g. Krüls and Achterberg, 1994; Langner, 2004; Strauss, 2010].

2.8 Diffusion

The local HMF can be written as

$$\vec{B}' = \vec{B} + \delta\vec{B}, \quad (2.8)$$

where $\vec{B}$ is the global (large scale) HMF and $\delta\vec{B}$ denotes a turbulent fluctuating component such that $\langle \delta\vec{B} \rangle = 0$ after an appropriate averaging process. CRs, as charged particles, will obey the Lorentz law while propagating in the global HMF, while the fluctuating component will cause changes to the particles' pitch-angle, leading to spatial diffusion. For example, the pitch-angle averaged diffusion coefficient directed parallel to the mean HMF is calculated as

$$\kappa_{\parallel} = \frac{v^2}{8} \int_{-1}^1 \frac{(1 - \mu^2)^2}{D_{\mu\mu}(\mu)} d\mu, \quad (2.9)$$

where $D_{\mu\mu}(\mu)$ is the Fokker-Planck pitch-angle diffusion coefficient, μ is the cosine of the pitch angle and v is particle speed [e.g. *Schlickeiser, 2002*]. In order to calculate $D_{\mu\mu}(\mu)$, the underlying HMF turbulence must be known and coupled to a particle scattering theory. The evolution of HMF turbulence, driven mostly by the Sun, can be modelled by applying a turbulence transport model [as discussed by e.g. *Oughton et al., 2011; Zank et al., 2012*], while, to calculate $\kappa_{\parallel}$, quasi-linear theory [e.g. *Jokipii, 1966*] is usually adopted. For the diffusion coefficient directed perpendicular to the mean HMF, non-linear guiding center theory is mostly implemented [*Matthaeus et al., 2003*]. In recent times, the coupling of a turbulence evolution model to a scattering theory in order to calculate the diffusion coefficients, and using these values to model CR propagation in the supersonic solar wind, have had some success [e.g. *Engelbrecht, 2013*]. However, some aspects of these models are still not completely understood, e.g. the inclusion of the TS and heliosheath, while the resulting models are very cumbersome and make the interpretation of the resulting CR intensities very difficult. In this thesis, a phenomenological approach is followed when choosing the diffusion coefficients for illustrative purposes, while it must be noted that these phenomenological forms of the diffusion coefficients usually compare quite well with the theoretical calculations [e.g. *Effenberger et al., 2012*]. Note that for each κ , a corresponding mean free path can be defined as

$$\kappa = \frac{v}{3} \lambda \quad (2.10)$$

with λ mostly prescribed in each of the following chapters.

The 3D diffusion tensor present in Eq. 2.7 is usually defined in terms of HMF aligned coordinates in a Parker HMF geometry as

$$\mathbf{K}_{HMF} \equiv \begin{bmatrix} \kappa_{||} & 0 & 0 \\ 0 & \kappa_{\perp\theta} & 0 \\ 0 & 0 & \kappa_{\perp r}, \end{bmatrix} \quad (2.11)$$

with one axis parallel to the mean HMF in the $r\phi$ -plane ($\mathbf{e}_{||}$), another perpendicular to the first in the $\mathbf{e}_\theta$ direction ($\mathbf{e}_1$) and the last lying in the $r\theta$ -plane, completing the right handed coordinate system ($\mathbf{e}_2$). The diffusion tensor must therefore be transformed to the coordinates system in which the TPE will be solved. For instance, this coordinate system is related to the spherical coordinate system through the HMF spiral angle Ψ as

$$\begin{aligned} \mathbf{e}_{||} &= \cos \Psi \mathbf{e}_r - \sin \Psi \mathbf{e}_\phi \\ \mathbf{e}_1 &= \mathbf{e}_\theta \\ \mathbf{e}_2 &= \mathbf{e}_{||} \times \mathbf{e}_1 \\ &= \sin \Psi \mathbf{e}_r + \cos \Psi \mathbf{e}_\phi. \end{aligned} \quad (2.12)$$

$\mathbf{K}$ can thus be written in spherical coordinates by specifying the appropriate transformation matrix

$$\mathbf{T} \equiv \begin{bmatrix} \cos \Psi & 0 & \sin \Psi \\ 0 & 1 & 0 \\ -\sin \Psi & 0 & \cos \Psi \end{bmatrix}, \quad (2.13)$$

with

$$\det(\mathbf{T}) = 1. \quad (2.14)$$

This allows the diffusion tensor to be written in spherical coordinates as

$$\begin{aligned} \begin{bmatrix} \kappa_{rr} & \kappa_{r\theta} & \kappa_{r\phi} \\ \kappa_{\theta r} & \kappa_{\theta\theta} & \kappa_{\theta\phi} \\ \kappa_{\phi r} & \kappa_{\phi\theta} & \kappa_{\phi\phi} \end{bmatrix} &= \mathbf{T} \mathbf{K}_{HMF} \mathbf{T}^T \\ &= \begin{bmatrix} \cos \Psi & 0 & \sin \Psi \\ 0 & 1 & 0 \\ -\sin \Psi & 0 & \cos \Psi \end{bmatrix} \begin{bmatrix} \kappa_{||} & 0 & 0 \\ 0 & \kappa_{\perp\theta} & 0 \\ 0 & 0 & \kappa_{\perp r} \end{bmatrix} \begin{bmatrix} \cos \Psi & 0 & -\sin \Psi \\ 0 & 1 & 0 \\ \sin \Psi & 0 & \cos \Psi \end{bmatrix} \\ &= \begin{bmatrix} \kappa_{||} \cos^2 \Psi + \kappa_{\perp r} \sin^2 \Psi & 0 & (\kappa_{\perp r} - \kappa_{||}) \cos \Psi \sin \Psi \\ 0 & \kappa_{\perp\theta} & 0 \\ (\kappa_{\perp r} - \kappa_{||}) \cos \Psi \sin \Psi & 0 & \kappa_{||} \sin^2 \Psi + \kappa_{\perp r} \cos^2 \Psi \end{bmatrix}, \end{aligned} \quad (2.15)$$

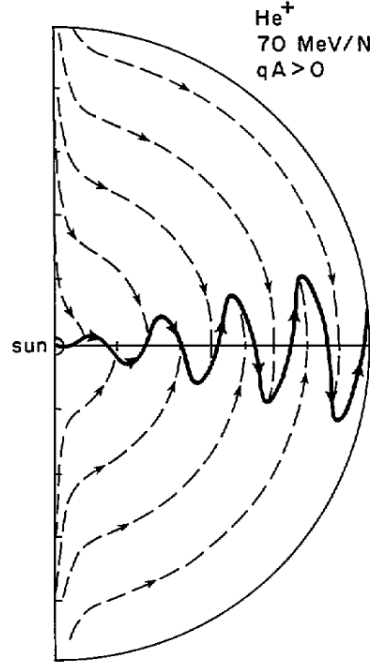


Figure 2.7: Average drift velocity streamlines in the meridional plane of the heliosphere for positive particles in the $A > 0$ magnetic polarity cycle. The drift directions will reverse for negatively charged particles, as well as for the $A < 0$ polarity cycle. The figure is taken from *Pesses et al.* [1981].

where the superscript T denotes the transpose of a matrix. A similar, but more general transformation is discussed in Chapter 8 to Cartesian coordinates, while *Effenberger et al.* [2012] discussed a different, but equivalent (when isotropic perpendicular diffusion is considered) approach to such transformations.

2.9 Particle Drifts

Due to the large scale HMF, CRs will undergo a combination of gradient, curvature and current sheet drift, the latter resulting because of the switch in HMF polarity across the HCS [e.g. *Burger and Potgieter, 1989*]). Drifts were neglected in modulation models until *Jokipii et al.* [1977] pointed out that drifts may indeed play a dominant role in CR modulations and can explain the observed HMF polarity dependent CR observations [e.g. *Jokipii and Kopriva, 1979; Potgieter and Moraal, 1985*]. See also Section 2.10.1 of this chapter, as well as the discussion in Chapter 7.

In the most general case the pitch angle averaged guiding centre drift velocity is given by

$$\vec{v}_d = \frac{p'v}{3q} \frac{(\omega\tau_d)^2}{1 + (\omega\tau_d)^2} \nabla \times \frac{\vec{B}}{B^2}, \quad (2.16)$$

where the suppression of drifts by turbulence (scattering) is included [see *Minnie et al., 2007*, and references therein]. Here, ω is the particle gyro-frequency, τ_d is some time scale defined by

scattering, q is the charge of the CR population under consideration and p' is particle momentum. Note that because $\nabla \cdot \vec{B} = 0 \Rightarrow \nabla \cdot \vec{v}_d = 0$. Eq. 2.16 can be rewritten as

$$\begin{aligned}\vec{v}_d &= \nabla \times \frac{p'c}{q} \frac{v}{c} \frac{1}{3B} \frac{(\omega\tau_d)^2}{1 + (\omega\tau_d)^2} \frac{\vec{B}}{B} \\ &= \nabla \times \frac{v}{3} r_L \frac{(\omega\tau_d)^2}{1 + (\omega\tau_d)^2} \mathbf{e}_B,\end{aligned}\tag{2.17}$$

in terms of the maximal Larmor radius

$$\begin{aligned}r_L &\equiv \frac{mv}{qB} \\ &= \frac{P}{Bc},\end{aligned}\tag{2.18}$$

and where $\mathbf{e}_B \equiv \vec{B}/B$ is a unit vector directed along $\vec{B}$.

Neglecting scattering, the drift velocity is usually taken to assume its maximal weak scattering value. Weak scattering, or the assumption that a particle undergoes a large number of gyrations before being scattered, leads to the approximation

$$(\omega\tau_d)^{ws} \gg 1.\tag{2.19}$$

With this assumption Eq. 2.17 reduces to

$$\begin{aligned}\vec{v}_d^{ws} &= \nabla \times \frac{v}{3} r_L \mathbf{e}_B \\ &= \nabla \times \kappa_d \mathbf{e}_B,\end{aligned}\tag{2.20}$$

with the weak-scattering drift coefficient introduced as

$$\kappa_d^{ws} \equiv \frac{v}{3} r_L.\tag{2.21}$$

For very strong scattering $(\omega\tau_d)^{ss} \rightarrow 0$, and it follows that $\kappa_d^{ss} \rightarrow 0$ and no particle drift is present. The drift coefficient can be expressed in terms of the so-called drift scale, defined by

$$\lambda_d \equiv \kappa_d \frac{3}{v}.\tag{2.22}$$

Note also that for the weak scattering case, the drift scale reduces to $\lambda_d^{ws} = r_L$.

Assuming weak scattering in a Parker HMF, Eq. 2.16 can be solved analytically to give

$$\begin{aligned}
 \vec{v}_d &= \vec{v}_{gc} + \vec{v}_{ns} \\
 &= \frac{2vp'r}{3qA(1+\gamma^2)^2} \left[-\frac{\gamma}{\tan\theta} \mathbf{e}_r + (2+\gamma^2) \gamma \mathbf{e}_\theta + \frac{\gamma^2}{\tan\theta} \mathbf{e}_\phi \right] \cdot |H(\theta - \theta')| \\
 &+ \frac{2vp'r}{3qA(1+\gamma^2)} [\gamma \mathbf{e}_r + \mathbf{e}_\phi] \cdot \delta(\theta - \theta').
 \end{aligned} \tag{2.23}$$

Note the factor qA in these expressions, which causes the drift velocity to change direction between magnetic cycles ($A = \pm 1$), while also changing sign for differently charged CR species ($q = \pm 1$). This leads to so-called charge-sign dependent modulation of CRs; a topic investigated extensively throughout this thesis. The second term in this equation, the neutral sheet drift velocity, must however be averaged over $4r_L$ because a CR will experience the HCS even when it is $2r_L$ away from it (on either side). For a flat HCS, $\vec{v}_{ns}$ changes to

$$\vec{v}_{ns} = v_{ns} (\sin \Psi \mathbf{e}_r + \cos \Psi \mathbf{e}_\phi) \cdot qA, \tag{2.24}$$

and is directed parallel to the HCS and perpendicular to the mean HMF thereby fulfilling $\nabla \cdot \vec{v}_d = 0$. The drift speed along the HCS is taken from *Burger et al.* [1985],

$$v_{ns} = \left\{ 0.457 - 0.412 \frac{|L|}{r_L} + 0.0915 \frac{|L|^2}{r_L^2} \right\} v \tag{2.25}$$

where $-2r_L \leq L \leq 2r_L$ is the minimum distance from the particle's position to the HCS.

The drift formalism discussed in this section is extended to the case of a wavy HCS in Chapter 7, while drifts in a non-Parkerian HMF are discussed and illustrated in Chapter 8.

2.10 Selected Cosmic Ray Cycles and Periodicities

Note that, in the section to follow, only CR cycles relevant to this thesis are discussed. For additional details regarding this topic, see e.g. *Potgieter* [2008b].

2.10.1 Solar and Magnetic Polarity Cycle Related Effects

The temporal behaviour of CRs have been studied over the last five decades by making use of neutron monitors (NMs) located in the Earth's surface [e.g. *Krüger*, 2006]. Fig. 2.8 shows the Hermanus NM counting rate (normalized to 100% in March 1987) as a function of time. The vertical dashed lines on Fig. 2.8 indicate times of solar maximum activity conditions, i.e. times when the HMF polarity reverses.

The ~ 11 year cycle is very pronounced in the NM observations, with higher counting rates observed during solar minimum conditions, and decreasing at times of solar maximum. Modelling the temporal behaviour of GCRs is discussed by e.g. *le Roux and Potgieter* [1995], *Ferreira*

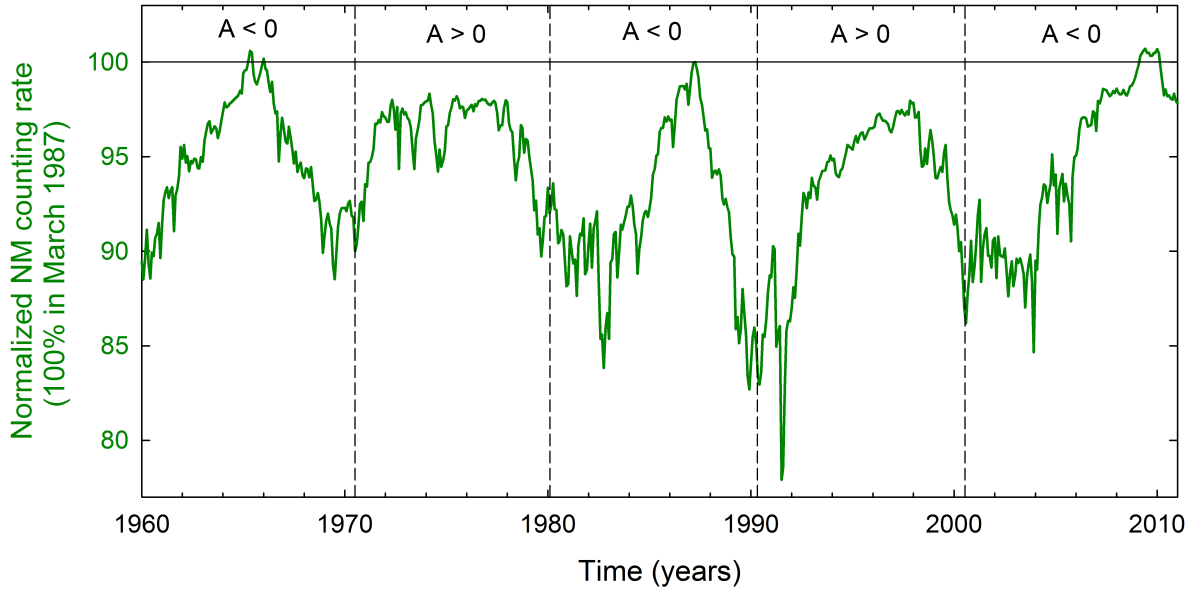


Figure 2.8: The normalized Hermanus NM counting rate as a function of time. The vertical lines indicate times of solar maximum conditions when the solar magnetic polarity switches.

and Potgieter [2004] and Manuel *et al.* [2011] and is essentially due to a time dependence in the diffusion coefficients: At times of solar maximum conditions, the HMF magnitude, as well as the levels of turbulence contained in the HMF, is larger, leading to smaller diffusion coefficients, which in turn leads to more heliospheric shielding of CR and lower intensities observed at Earth.

A ~ 22 year cycle, related to the solar magnetic cycle, is also evident in the NM counts. During times of $A < 0$ HMF polarity (i.e. $\sim 1960 - 1971$, $\sim 1980 - 1991$, $\sim 2001 - \text{present}$) the temporal profile of the NM counts shows a peaked (sharp) maximum during solar minimum conditions, which becomes rather flattish during times of $A > 0$ HMF polarity (i.e. $\sim 1971 - 1980$, $\sim 1991 - 2001$). These alternating sharp and broad peaks are caused by the different drift fields in alternating HMF cycles [e.g. Jokipii *et al.*, 1977; Potgieter, 1984; Potgieter and Moraal, 1985] and are discussed and illustrated again in the following chapters.

2.10.2 A ~ 13 Month Electron Periodicity

The first hint that Jupiter might be a strong source of low energy electrons was observed at Earth as a ~ 13 month periodicity in the low energy electron counting rate. Fig. 2.9 shows such observations presented by Sternal [2010]. This electron periodicity is correlated with the ~ 13 month synodic period of Jupiter and is therefore related to the level of magnetic connection between Jupiter and Earth. This effect is modelled and discussed in detail in Chapter 6.

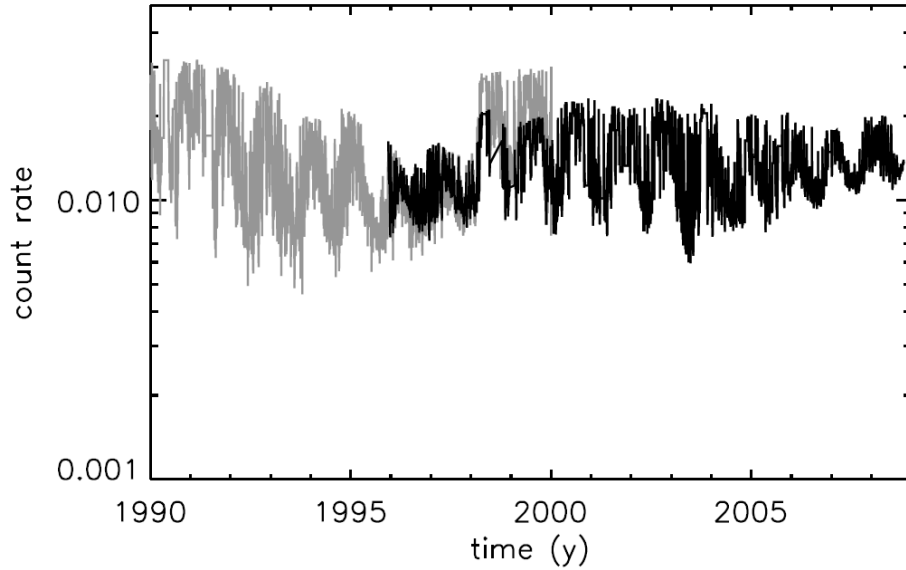


Figure 2.9: The electron counting rate of the IMP-8 (grey) and SOHO (black) spacecraft as a function of time at ~ 7 MeV, illustrating the ~ 13 month electron periodicity as observed at Earth. The figure is taken from *Sternal* [2010].

2.11 Summary

The solar wind, embedded HMF and the HCS were introduced and discussed. In the next chapter, it will be shown how the outflow of the magnetized solar wind interacts with the interstellar medium to form the heliosphere, while the structure of the heliosphere is also discussed in greater detail. The main CR species that will be modelled in this thesis were introduced and discussed, along with the basic TPE (and the processes contained in this equation) governing their heliospheric transport. Lastly, the temporal behaviour of the heliosphere, and the resulting impact thereof on CR intensities at Earth, were shown and discussed.