Abstract

The PAMELA satellite has observed an excess of positrons over electrons in the energy range \(1 - 100 \text{ GeV}\) that increases with energy. We propose that the excess is not due to a change in the local interstellar spectrum, but is due to heliospheric modulation. We motivate this from the known form of the heliospheric magnetic field and predict that the excess will disappear when we enter a period of solar maximum activity.

1 Introduction

The PAMELA satellite [1] has observed a rise in the positron to electron fraction that increases with energy above 10 GeV. This has been interpreted as proof of a rise in the positron fraction in the local interstellar spectrum of cosmic rays. Such a result requires that there be some hardening of the positron spectrum at these energies and has caused a great deal of discussion of possible sources from decaying or annihilating dark matter to acceleration from a population of pulsars.

We propose instead that this rising fraction is due to the heliospheric magnetic field. The heliospheric magnetic field is ordered over large distances during solar minimum [2, 3] and is well described up to medium latitudes by a Parker spiral field [4]. During solar minimum this means that for a particle to propagate directly to earth it must traverse a large scale ordered magnetic field that is primarily oriented perpendicularly to the radial. Direct transport is impossible for low energy particles \( (E < 1 \text{ GeV})\) as their Larmor radius is small even in the outer heliosphere. They instead reach the central solar system primarily by following the magnetic field lines along with a complex process involving convection, diffusion, drifts and energy loss. At high energies \( (E > 1 \text{ TeV})\), particles can traverse the ordered magnetic field with little deviation. At these energies we see the interstellar spectrum directly.

If the magnetic field were the only effect on the particle transport, and if the magnetic field were time invariant, then the switch from one set of particles paths to the other

\[\text{E-mail: jonathan.roberts@nyu.edu}\]
would have no effect on the flux by Liouville’s theorem. However the magnetic field is
time variant. The magnetic field lines are carried by the supersonic solar wind and travel
out towards the edge of the heliosphere at 400 km/s. This causes large scale convection of
cosmic rays that results in a deficit in the cosmic ray density in the central solar system
when compared to the interstellar spectrum. This has been well measured for cosmic rays
with rigidities up to 2.5GV \[3, 5\]. At these rigidities, the particles generally have a very
long path length to the center of the solar system as they follow the magnetic field lines.
Therefore they have a low radial velocity, and are greatly effected by the convection of
the solar wind. The solar magnetic field also varies on longer timescales, affected by the
27 day rotation period of the sun, and by the reversal of the solar magnetic field every 11
years.

At higher rigidities particles can travel directly to the central solar system at the speed
of light. Their path length within the heliosphere is short and they are almost unaffected
by convection from the solar wind. Therefore at high energies we expect there to be
no radial gradient of cosmic rays as they should free stream through the solar system.
From these two observations - the two separate transport paths for low and high energy
particles, and radial gradient of low rigidity cosmic rays from the convection of the solar
wind - we can already say that there must be a hardening of the cosmic ray spectrum
between rigidities of 1 GV and 1000 GV. This will be due to the change over from a
locally suppressed cosmic ray flux to the interstellar flux.

To explain the PAMELA signal we need one further element. We require that the
change over from the local flux to the interstellar flux be charge asymmetric. We already
know that the orientation of the magnetic field results in asymmetric cosmic ray transport.
Indeed this is the cause of the low energy heliospheric modulation below a few GeV [6]. We
argue that this is also true for high energy particles and that the asymmetry should become
more pronounced with increasing energy. We use a simple model of the heliospheric
magnetic field to show this in section 4.1. This exhibits the primary features of the
asymmetry that we are interested in. We then extend the study to consider the asymmetry
in a more complex realisation of the field in section 4.2.

By postulating a heliospheric cause of the positron excess we can immediately make
a clear prediction. We predict that the excess should disappear when the solar system
enters a period of solar maximum activity which it is due to do shortly. In addition, in
the opposite solar cycle when the sun’s magnetic field is oppositely aligned, we would
expect to see the opposite modulation - giving a rising excess of electrons over positrons
in the energy range 1 – 100 GeV. We will also show that the tilt angle of the heliospheric
current sheet (HCS) is an important feature of the model, and predict that any temporal
variation of the latitudinal extent of the current sheet should be matched by a variation
in the observed positron excess, with a time delay due to the time taken for magnetic field
features at the sun to propagate out to the heliopause in the solar wind. These predictions
are robust features of our model and testable in the near future.
2 The heliospheric magnetic field

In 1958 E. N. Parker proposed that the solar system magnetic field took the form of an Archimedes spiral [4]. The sun is a rotating dipole and the magnetic field is carried out into the solar system by the supersonic solar wind. As the solar wind travels out from the sun its rotational velocity slows with respect to the plasma at the surface of the sun, causing it to be retarded and dragging the magnetic field into a spiral. This continues out to the termination shock at around 80 AU where the solar wind becomes subsonic.

The heliospheric magnetic field is described in the Parker model by:

$$B = B_0 \frac{r_0^2}{r^2} \left[ \hat{e}_r - \frac{\Omega_\odot (r - b) \sin \theta}{V} \hat{e}_\phi \right],$$

where \((r, \theta, \phi)\) are heliocentric spherical coordinates, \(B_0\) is the magnetic field at \(r_0\), \(V\) is the solar wind speed, \(b\) is the radius at which the field is purely radial and \(\Omega_\odot\) is the equatorial rotation of the sun.

The Parker model is very successful at modeling the magnetic field at moderate latitudes during times of solar minimum activity. More sophisticated models that perform better at high latitudes and times of greater solar activity have since been proposed. One widely used model is due to Fisk [7]:

$$B = B_0 \frac{r_0^2}{r^2} \left[ \hat{e}_r - \frac{r \omega_\theta}{V} \hat{e}_\theta - \frac{(\Omega_\odot - \omega_\phi) r \sin \theta}{V} \hat{e}_\phi \right],$$

where \(\omega_\theta\) and \(\omega_\phi\) are the differential rotation rates in the \(\theta\) and \(\phi\) direction respectively [8].

In both cases the magnetic field is essentially a spiral. The field lines are oriented radially close to the sun’s surface. At large radii they are predominantly azimuthal. The winding of the magnetic field causes it to remain strong to large radii, with the strength of the azimuthal component falling off as \(1/r\). The solar magnetic field is also oppositely aligned in the northern and southern hemisphere, with a sheet of zero magnetic field separating the two. This is known as the heliospheric current sheet (HCS).

The sun’s magnetic poles are not aligned with its axis of rotation. This means that the HCS is tilted at the sun and that this tilt varies as the sun rotates. These variations are carried out into the solar system by the solar wind they cause the current sheet to be rippled. As the variations are carried out radially the latitudinal extent of the current sheet is described by a tilt angle \(\theta_t\). At times of solar minimum, the tilt angle is small, often around \(5 - 10^\circ\). At times of solar maximum the tilt angle grows to large values, before the solar polarity flips and the new polarity is carried out to the heliopause by the solar wind [9].
We are currently in a period of solar minimum and the magnetic field is shown schematically in Fig. 1. The heliospheric magnetic field has been well mapped by a number of satellites as well as by ground based observatories. The current field configuration means that the field lines are directed in towards the sun in the northern hemisphere and outward from the sun in the southern hemisphere. The local magnetic field at earth in around $3.3 \text{nT}$. For a review see [3].

### 3 Cosmic ray propagation through the heliosphere

To consider the motion of galactic cosmic rays through the heliosphere let’s first state the equation for the Larmor radius of a relativistic particle in a magnetic field in convenient units:

$$ r_g(AU) = \frac{2.2 \times 10^{-2} p_{\perp}(\text{GeV}/c)}{|q|B(nT)}. \quad (3) $$

If we take the magnetic field strength (at low latitudes) to be $|B| = B_E/r(AU)$ and the local field strength at earth over the course of the PAMELA data to be $B_E = 3.3 \text{nT}$ then we can approximate the Larmor radius of a particle at low latitudes to be:

$$ r_g(AU) = 6.67 \times 10^{-3} p_{\perp}(\text{GeV}/c)r(AU), \quad (4) $$

where $r$ is just the distance from the center of the solar system.
From this we can see that a singly charged particle with a rigidity of 1 GV has a Larmor radius of less than 1 AU even in the weak magnetic field near the termination shock at 80 AU. There is no means for such a particle to propagate directly to the center of the solar system. At the other extreme, a 1 TeV particle has $r_g = 6.7r$ at all $r$. As $r_g \gg r$ at all points on its path, it can penetrate the center of the solar system with relatively little deflection in its trajectory (around $10^\circ$). At energies above a few tens of TeV the deflection becomes negligible and we can truly say that any effect of the heliospheric magnetic field should disappear.

In between these two limits we must consider two separate populations of cosmic rays:

1. those that travel to the center of the solar system by traveling along magnetic field lines
2. those that can penetrate the center of the solar system by traveling perpendicular to the magnetic field.

At high energies we know that the flux of cosmic ray must be approximately homogeneous and isotropic. The flux that we see should correspond directly to the interstellar spectrum.

The same cannot be said of the low energy cosmic rays. The transport of sub-$GeV$ cosmic rays within the solar system is described by the transport equation - first proposed by Parker in 1965 [10]:

$$\frac{\partial U}{\partial t} = -\nabla \cdot (C V U) - \nabla \cdot (\langle v_d \rangle U) + \nabla \cdot (\kappa^{(S)} \cdot \nabla U) - \frac{1}{3} \frac{\partial}{\partial p} (p V \cdot \nabla U),$$  \hspace{1cm} (5)

where $U$ is the density of cosmic rays as a function of position, momentum and time, $V$ represents the solar wind velocity, $C = 1 - (1/3U)\partial/\partial p(pU)$ is the Compton-Getting coefficient, $\langle v_d \rangle$ is the averaged drift velocity and $\kappa^{(S)}$ is the symmetric part of the diffusion tensor:

$$\kappa = \begin{pmatrix} \kappa_{||} & 0 & 0 \\ 0 & \kappa_{\perp} & \kappa_{T} \\ 0 & -\kappa_{T} & \kappa_{\perp} \end{pmatrix}.$$ \hspace{1cm} (6)

The terms on the right hand side of the transport equation represent the change in particle density over time. The first term represents convection caused by the solar wind carrying particles out of the solar system towards the edges. This effect is large when the average radial velocity of a particle is of the same order or smaller than the solar wind speed. The second term quantifies the effects of drifts - where a variation in the magnetic field strength allows for a motion of the particles in the direction of $\nabla \times B$. These drifts are large scale particle motions and are modeled as effective sources or sinks in the system. They only affect the particle density if $\nabla U$ is non-zero. Convection ensures a
radial gradient in the cosmic ray density and makes drifts a critical element of low energy cosmic ray transport. The third term covers diffusion - modeling the scattering of particles off inhomogeneities in the magnetic field. The terms in the diffusion matrix are not well known. For low energy transport, perpendicular diffusion is taken to be significantly less efficient than parallel diffusion ($\kappa_\perp \approx 0.02\kappa_{||}$). The final term represents adiabatic energy changes. The solution of this equation in 3D requires sophisticated numerical simulations which we will not discuss further here. For a review of recent work in this area see [8, 11].

For our purposes it is enough to note that the transport of low energy cosmic rays is very different from the transport of high energy cosmic rays. The average radial velocity of low energy cosmic rays is small - through perpendicular diffusion and drifts - and therefore the convection effects of the solar wind create a radial gradient in the cosmic ray density. This is well measured for low energy cosmic rays ($E < 200\ MeV$) and was analysed over different solar minima and maxima in [12]. The gradient has also been measured for protons and electrons with higher rigidities along the Ulysses trajectory [5]. In the inner heliosphere electrons and protons with rigidities of 2.5GV were shown to have a radial gradient of $2 - 3%/AU$ at solar minimum. In contrast we know that there cannot be any radial gradient at very high energies when the cosmic rays free stream through the solar system.

We will take the approximation that the local density of cosmic rays that travel to the center of the solar system along the field lines to be suppressed with respect to the total interstellar flux by a factor $A$:

$$F_{1AU} = AF_{80AU}$$

This remains true up to 450 GeV when the particles can penetrate the central solar system directly. Clearly this is an approximation as particles will penetrate further into the solar system as their energy increases, affecting the overall flux before we reach 450 GeV. However within the energy we are interested in for PAMELA, we expect the approximation to be good as the Larmor radii remain small compared to the distance travelled.

This energy dependent flux deficit would have little bearing on the PAMELA result if there was a smooth transition from one propagation method to the other. However, the form of the magnetic field allows some particles to penetrate directly into the central solar system even at low energies, and this effect is charge asymmetric.

4 The magnetic lense

4.1 A flat current sheet

Let us consider a magnetic field that is purely azimuthal and has a strength that falls off as $B_E/r(AU)$. Let us further take the approximation of a flat current sheet in the ecliptic
We show paths of positively charged particles that cross the ecliptic plane in the approximation of a flat current sheet and a simplified magnetic field. Note that it does not matter at what angle the particle crosses the ecliptic plane, the overall motion is always towards the center of the solar system.

In this magnetic field, the Larmor radius of the particle is given by:

\[ r_g(AU) = \frac{2.2 \times 10^{-2} p_t(GeV/c) r(AU)}{|q|B_E(nT)}. \tag{8} \]

In Fig. 2 we show a schematic of the paths of positively charged particles that cross the ecliptic in the current magnetic field configuration. For any particle that crosses the ecliptic, its overall motion is towards the center of the solar system. For particles of the opposite sign the motion of a particle that crosses the ecliptic is away from the center of the solar system.\(^1\)

\(^1\)We are certainly not the first to notice this effect. Indeed it was first shown to exist by Levy in 1976 \[^{13,14}\]. He noted that there should be a large charge asymmetry and that this should exist up to large
As the Larmor radius decreases with the distance from the center of the solar system we can define the volume within which the particles can travel directly to the center of the solar system. The fractional volume is just given by the opening angle:

\[ f = \frac{r_g}{r} = \sin \theta = \frac{2.2 \times 10^{-2} p_\perp (GeV/c)}{|q|B_E (nT)} \] (9)

where \( f = \sin \theta \) gives the fraction of the total solid angle that allows particles to travel through the ecliptic in this manner.²

Clearly this formula is not valid at large angles as we would need to carefully treat the varying Larmor radius of the particle over the course of one rotation due to the latitudinal variation in the magnetic field. Here we are considering only particles within the ranges of the PAMELA measurements, which corresponds to an opening angle of 33 degrees, small enough that these corrections can be neglected in our rough approximation.

Within this volume there is a population of cosmic rays that arrive at the center of the solar system traveling perpendicular to the magnetic field lines rather than along them. This population has a radial velocity close to the speed of light and thus the effects of convection should be negligible. In addition, the overall flow of the opposite sign particles out of the solar system results in a relative decrease in the number density of oppositely charged particles. We model the result of this by taking the fluxes of the two populations of cosmic rays to be:

\[ F_{1 \, AU}(e^+) = (A + f)F_{80 \, AU}(e^+) \]
\[ F_{1 \, AU}(e^-) = AF_{80 \, AU}(e^-) \] (10)

where \( f \) is the fraction of the particles in the heliosphere on a trajectory that allows them to travel across the HCS, and \( A \) is the suppression of the local flux with respect to the interstellar flux.³

²As we saw in Fig. 2, particles that are up to \( 2r_g \) from the ecliptic can cross the ecliptic and drift towards the center of the solar system. However as you consider particles at increasing distances from the ecliptic, the range of angles that allow the particle to reach the ecliptic decreases. The fraction of particles at a height \( d \) from the ecliptic that have trajectories that can cross it is given by \( 1/\pi \cos^{-1}(d - r_g) \). When we integrate over this distribution we find that \( 1/2 \) of all particles in the volume defined by the angle \( -2\theta \rightarrow 2\theta \) have trajectories that can cross the plane. This gives the total fraction of the particles to be \( \sin \theta \).

³Here we consider electrons and positrons, but we note that the same arguments can be made for other cosmic ray species. Specifically we would expect to see a deficit of anti-protons in the current solar minimum. For protons and anti-protons we cannot approximate rigidity with energy and we expect the
Figure 3: Using Eq. 10, we fit the PAMELA spectrum. We use a standard background spectra generated using Galprop [15, 16].

Using this model we fit to the PAMELA data in Fig. 3. This fit requires that the local flux be 23% of the interstellar flux, though the large error bars on the high energy points allow for a wide range of values (14% to 30%) for the local suppression. In addition there is substantial uncertainty in the background spectrum which will have an effect on any fit. Nevertheless, we note that though the fit accounts for the rising profile of the high energy fraction, it does not correctly model the behaviour below 20 GeV, instead giving a result that is significantly too high. This is not particularly surprising given the rough and ready nature of our toy model for the magnetic field.

4.2 An oscillating current sheet

In the previous section we considered a simplified magnetic field with a flat current sheet. This is clearly not realistic - we know that the current sheet oscillates and extends to
large heliolatitudes. Even at solar minimum the current sheet extends up to around 15°
(from the Wilcox Solar Observatory [17]). The tilt varies considerably from month to
month. However we will consider an idealised situation where the tilt remains constant
throughout the heliosphere to qualitatively understand the effect of the tilted current
sheet on the high energy cosmic ray flux.

Figure 4: A schematic diagram of the particle paths in the magnetic field with an oscillating
current sheet. Particles of both signs can penetrate the center of the solar system along the ecliptic
plane once their momentum is large enough that their Larmor radius exceeds the wavelength of
the current sheet. Particles with a large Larmor radius that leave the angular volume described
by the ecliptic have paths that are equivalent to the scenario of a flat current sheet just as before,
providing an excess of one charge over the other.

We show a schematic diagram of high energy particle paths in Fig. 4. In modulation
theory [18] the effect of the oscillating current sheet is incorporated taking it to be a flat
sheet that gives rise to an overall drift velocity in the plane. The oscillations of the current
sheet have the effect of increasing the distance travelled by particles traveling along the
current sheet and consequently reducing the overall drift velocity. At low energies this
results in a drift velocity that is lower than the solar wind speed and the inward drift of
the cosmic rays is countered by the convection of the solar wind.

This works well as long as \( r_g \) is smaller than the wavelength of the current sheet (6.5 AU) at all points in the heliosphere. This is true for sub-GeV particles considered in classical heliospheric modulation. However as soon as \( r_g \) is greater than the wavelength a particle can pass directly along the ecliptic - as shown in Fig. 3. This is charge symmetric close to the ecliptic. This allows particles of both species to propagate deep into the heliosphere. As the Larmor radius goes as \( 1/r \), and the wavelength of the HCS remains constant with \( r \), a particle with a given energy will penetrate up to the point where \( r_g \) becomes less than the wavelength. At this point a positively charged particle (in the current solar phase) will continue to travel inwards along the current sheet, and a negatively charged particle will not. At a large enough energy, particles of both species will travel to the inner heliosphere in this manner.

The second effect to note is that for high energy particles that travel outside the volume containing the current sheet we still have the same asymmetric paths that cause positrons move to the center of the solar system and cause electrons to move towards the termination shock. This is to be expected, as when \( r_g \) is larger than the amplitude of oscillation there are many paths on which the positrons cross the current sheet only once per rotation. For these particles the oscillation of the current sheet is irrelevant and the effect should be identical to the case of a flat current sheet. For these particles we should see the effect that we considered earlier where positrons have a direct path to center of the solar system and electrons do not.

To accurately account for the variation in the cosmic ray species due to these complex paths will require a detailed computer model of the particle propagation. This is underway and will be presented in a future work. For now we construct an approximation to highlight the main effect of the oscillating current sheet:

- High energy particles that arrive at the ecliptic with relatively large incident angles will cross the current sheet only once per half rotation - at all points along their path of travel. In this case the current sheet is identical to a flat current sheet.

- High energy particles that have a gyroradius \( r_g > 6.5 \text{ AU} \) can pass radially through the volume containing the oscillating current sheet. This is true for particles of both signs and is also true in both directions. For these particles there is no charge dependent excess of one species over the other.

We model this effect by imposing a flat reduction in the fraction of the particles that can be considered to be crossing a flat current sheet.

\[
f' = \sin \theta - \delta, \quad f' \geq 0 \tag{11}
\]

where we expect \( \delta \) to be proportional to \( \sin \theta_t \) as the reduction is directly due to the latitudinal extent of the current sheet.
This does not account for the increase in the local flux that we should see above a few GeV in both electrons and positrons from their passage directly through the oscillating heliosheet along the ecliptic. However these increases are entirely charge symmetric so they will only have a small effect the ratio of fluxes. The more significant effect is to reduce the fraction of positrons that can be considered to be crossing a flat current sheet, and to effectively impose a low energy threshold below which no positrons can be considered to be traveling along a flat current sheet.

Taking this into account we now write the ratio of fluxes to be:

\[
\frac{\Psi_{1AU}(e^+)}{\Psi_{1AU}(e^+ + e^-)} = \frac{(A + f')F_{80AU}(e^+)}{((A + f')F_{80AU}(e^+) + AF_{80AU}(e^-)}.
\]

(12)

Figure 5: We fit the PAMELA data with a model that incorporates a varying current sheet. At low energies we do not expect a good fit as conventional heliospheric modulation effects dominate here.

We show the result in Fig. 5. This fit requires the local density to be 15% of the interstellar density and for \( \delta = 0.09 \). The oscillating current sheet has the effect of moving the rise in the positron fraction to larger energies, and decreasing the overall magnification effect of the lense.
Even though we have used a number of broad approximations the predictions are robust. It is true that there is an asymmetry in the propagation paths of particles of different signs at these energies. It is also clear that this asymmetry can only become significant once the Larmor radius of the particles is large with respect to the latitudinal extent of the current sheet, and once it does become significant it rises with energy. We only need to assume that there remains a radial gradient in the density of cosmic rays at these energies\(^4\) to predict a rising positron fraction between 10 and 100 GeV.

This allows us to make two predictions. Firstly, that the excess will disappear once we leave our current solar minimum. Secondly, we note that the tilt of the current sheet has a substantial effect on our model as it determines the energy at which the effect switches on. The tilt of the current sheet changes over time and as such provides us with an opportunity. We would predict a variation of the excess of positrons that correlates with large scale variations in the tilt of the current sheet, delayed by the time it takes for those variations to propagate out into the wider heliosphere.

5 Conclusions

We have proposed that the PAMELA positron excess is not down to annihilating dark matter or new astrophysical sources, but instead results from the configuration of the heliospheric magnetic field. The ordered nature of the magnetic field on large scales creates a lense that allows particles of one sign to free stream into the center of the solar system whilst particles off the opposite sign travel out. This effect rises with energy. It naturally occurs in the correct energy range for the correct sign of particle to account for the observed positron excess. Though our model of the solar system magnetic field is rough, we can already make two clear predictions. Firstly, the PAMELA result will disappear when we go through solar maximum (with a suitable delay to account for the time it takes the conditions at the sun to propagate out through the solar system). Secondly, we predict that there will be fluctuations in the observed excess that correlate (again with a delay) to the tilt angle of the heliospheric current sheet.

\(^4\)The radial gradient in cosmic ray densities should disappear for energies of a few TeV when particles free stream through the heliosphere. It is tempting to use this to explain the Fermi excess in cosmic ray electrons. In this case the bump at 500 GeV would be the observation of the unmodulated spectrum whereas the low energy data would represent the locally suppressed flux. To fit the Fermi data in this way would indicate the local flux at 10 GeV to be 60% of the unmodulated interstellar flux - 4 times the flux we use to fit the PAMELA signal. We note that there are many sources of uncertainty in our model that could account for this discrepancy and we will require that our more complete description should account for this difference. There also remains the possibility that there is an extra primary component to the electron and positron spectrums but that such an excess would be smaller than previously considered.
Acknowledgements

The work of JPR was supported by NSF Awards PHY-0758032 and PHY-0449818 and DoE Award No. DE-FG02-06ER41417. He would like to thank R. Johnson and E. J. Smith for advice on the heliospheric magnetic field, Ilias Cholis for discussions on interstellar spectra, Andre Gruzinov for discussions about Liouville’s theorem and Neal Weiner for many useful discussions about the PAMELA data. He would also like to thank the GGI and the INFN for their hospitality in Florence when this work was being completed.

References

[1] O Adriani, G Barbarino, and G Bazilevskaya. An anomalous positron abundance in cosmic rays with energies 1.5–100 gev. Nature, Jan 2009.

[2] Xiaoyan Zhou and Edward J Smith. Solar cycle variations of heliospheric magnetic flux. Journal of Geophysical Research, 114:03106, Mar 2009.

[3] Andre Balogh, Louis J. Lanzerotti, and Steven T. Suess. The Heliosphere through the Solar Activity Cycle. Springer, 2008.

[4] E. N Parker. Dynamics of the interplanetary gas and magnetic fields. Astrophysical Journal, 128:664, Nov 1958.

[5] D. C Ndiitwani, S. E. S Ferreira, M. S Potgieter, and B Heber. Modelling cosmic ray intensities along the ulysses trajectory. Annales Geophysicae, 23:1061, Feb 2005.

[6] M. S Potgieter, R. A Burger, and S. E. S Ferreira. Modulation of cosmic rays in the heliosphere from solar minimum to maximum: a theoretical perspective. Space Science Reviews, 97:295, May 2001.

[7] L. A Fisk. Motion of the footpoints of heliospheric magnetic field lines at the sun: Implications for recurrent energetic particle events at high heliographic latitudes. Journal of Geophysical Research, 101:15547, Jun 1996.

[8] R. A Burger. Cosmic-ray modulation and the heliospheric magnetic field. Advances in Space Research, 35:636, Jan 2005.

[9] J. Todd Hoeksema. The large-scale structure of the heliospheric current sheet during the ulysses epoch. Space Science Reviews, 72:137, Mar 1995.

[10] E. N Parker. The passage of energetic charged particles through interplanetary space. Planetary and Space Science, 13:9, Dec 1965.

[11] Stefan Ferreira. Theory of cosmic ray modulation. Proceedings of the International Astronomical Union, 4(S257):429–438, Dec 2008.
[12] Z Fujii and F. B McDonald. The spatial distribution of galactic and anomalous cosmic rays in the heliosphere at solar minimum. *Advances in Space Research*, 35:611, Jan 2005.

[13] E Levy. Origin of the twenty year wave in the diurnal variation. *International Cosmic Ray Conference*, 4:1215–1215, Jan 1975.

[14] E Levy. Theory of the solar magnetic cycle wave in the diurnal variation of energetic cosmic rays - physical basis of the anisotropy. *Journal of Geophysical Research*, 81:2082–2082–2088–2088, Jan 5.

[15] Andrew W Strong and Igor V Moskalenko. Propagation of cosmic-ray nucleons in the galaxy. *The Astrophysical Journal*, 509:212, Nov 1998.

[16] Ilias Cholis and Neal Weiner. Mixdm: Cosmic ray signals from multiple states of dark matter. *arXiv*, astro-ph.HE, Dec 2009.

[17] Wilcox Solar Observatory. http://wso.stanford.edu/tilts.html.

[18] R. A Burger and M. S Potgieter. The calculation of neutral sheet drift in two-dimensional cosmic-ray modulation models. *Astrophysical Journal*, 339:501, Apr 1989.