Effects of scattering parameters on charge-sign dependent cosmic ray modulation

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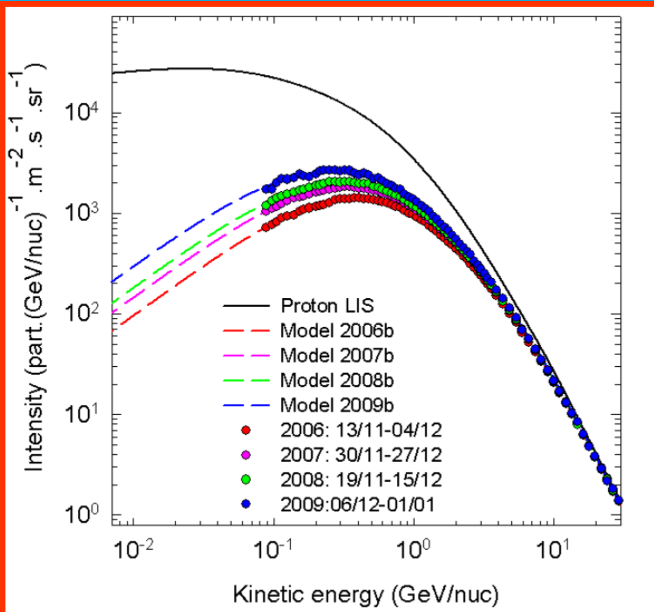
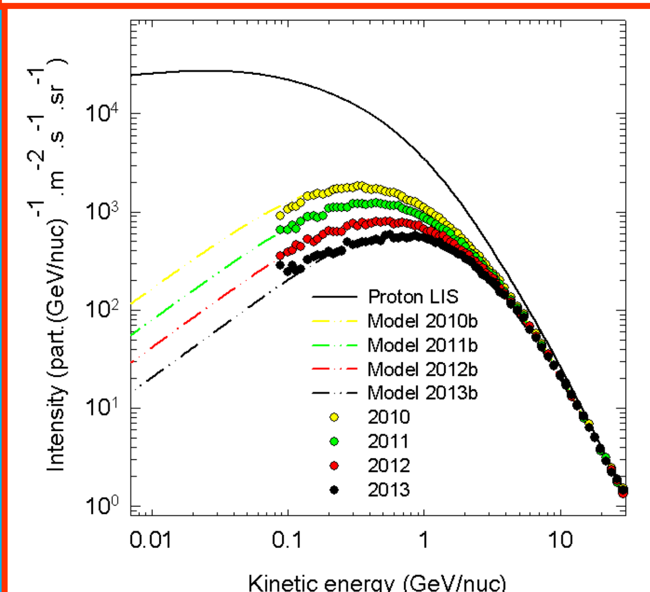
Introduction





- We apply the Measurement-Validated 3D numerical model (M-V Model) of Potgieter & Vos (2017) based on Parker's transport equation (TPE).

$$K_T = K_{A0}\frac{\beta P}{3B_m}\frac{(P/P_{A0})^2}{1+(P/P_{A0})^2} \;\Rightarrow\; K_T = \frac{\beta P}{3B_m}\left[\frac{(\omega\tau)^2}{1+(\omega\tau)^2}\right]$$

- To make meaningful comparison the modulation of both protons and anti-protons is done using the same set of modulation parameters and diffusion coefficients.

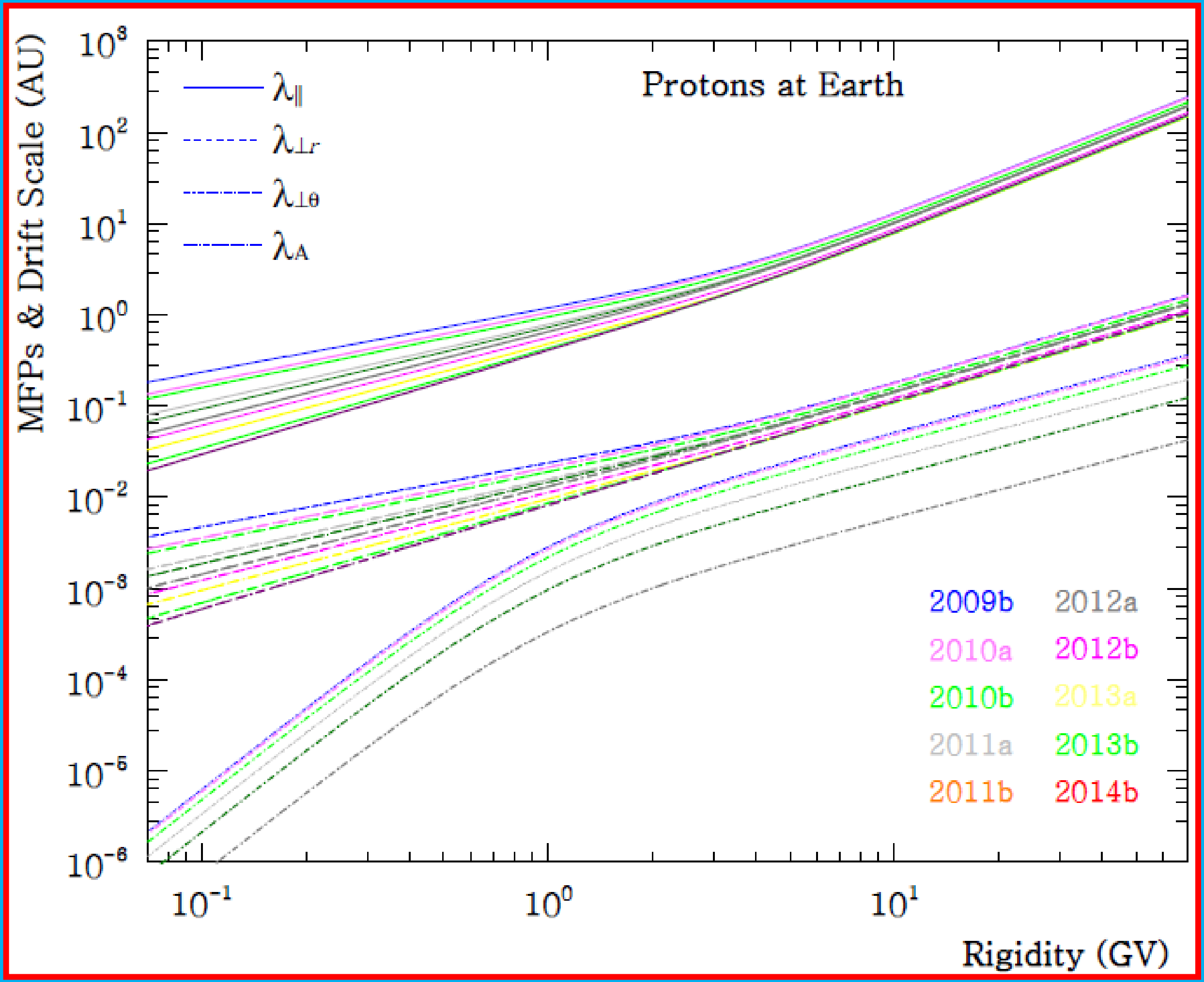
- We illustrate and discuss differences that exist between protons and anti-protons in their intensity-time profiles and ratios (p/pbar) from 2006 till the end of 2014 due to the assumed spatial dependence of $\omega\tau$.

Corresponding modulation parameters from 2009 to 2013

Table: Summary of the modulation parameters used to reproduce the **proton measurements** **2009b-2013b** from PAMELA.

Parameters	2009b	2010b	2011b	2012b	2013b
α (degree)	9.50	21.01	45.21	62.09	65.78
B(nT)	3.91	4.52	5.11	5.58	5.19
r_s (AU)	80.0	82.0	84.0	86.0	88.0
$\lambda_{\|\|}$ (AU)	1.185	1.090	0.948	0.798	0.565
K_{A0}	0.90	0.80	0.40	0.0	0.0
P_{A0} (GV)	0.90	0.90	0.90	0.90	0.90
$K^0_{\perp r}$	0.02	0.02	0.02	0.02	0.02
$K^0_{\perp \theta}$	0.02	0.02	0.02	0.02	0.02
c_1	0.70	0.77	0.89	0.96	1.09
$c_{2\|\|}$	1.52	1.52	1.52	1.52	1.52
$c_{2\perp}$	1.14	1.14	1.14	1.14	1.14
c_3	2.50	2.50	2.50	2.50	2.50
P_k (GV)	4.00	4.00	4.00	4.00	4.00
$d_{\perp \theta}$	6.00	6.00	6.00	6.00	6.00

Corresponding Mean Free Paths and Drift Scale



Transport equation for the modulation of cosmic rays in the heliosphere

Parker's (1965) Transport Equation (TPE):

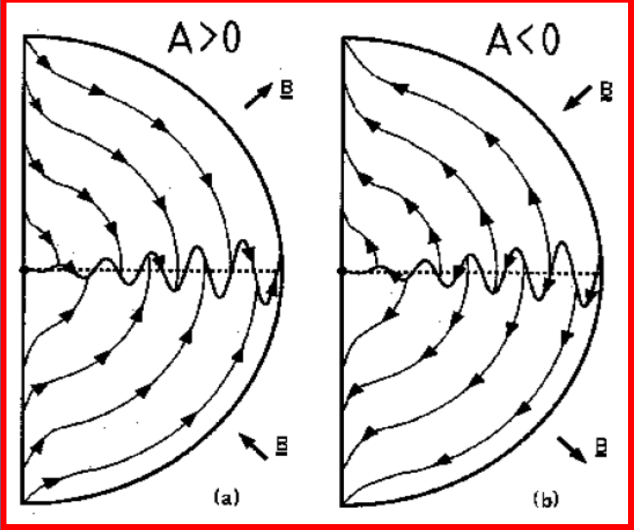
$$\frac{\partial f}{\partial t} = \nabla \cdot [\mathbf{K} \cdot \nabla f] - V \cdot \nabla f - \langle v_D \rangle \cdot \nabla f + \frac{1}{3}(\nabla \cdot V)\frac{\partial f}{\partial \ln p} + Q(r,p,t) \quad (1)$$

Diffusion **Convection** **Particle drifts** **Adiabatic energy changes** **sources**

$f(\mathbf{r},p,t)$ is the cosmic ray distribution function.

K is the diffusion tensor:

$$\mathbf{K} = \begin{bmatrix} K_{rr} & K_{r\theta} & K_{r\phi} \\ K_{\theta r} & K_{\theta\theta} & K_{\theta\phi} \\ K_{\phi r} & K_{\phi\theta} & K_{\phi\phi} \end{bmatrix}$$



$\mathbf{V}(r, \theta) = V(r, \theta)\mathbf{e}_r$ is the solar wind velocity vector

$\mathbf{v_D}$ is the averaged gradient and curvature drift velocity

The drift coefficient

In general: $$\langle \mathbf{v}_d \rangle = \nabla \times K_T \frac{\mathbf{B}}{B_m}$$ (1)

Bieber&Matthaeus, 1997

$$K_T = \frac{\beta P}{3B_m} f_s,$$ where $$f_s = \frac{(\omega\tau)^2}{1 + (\omega\tau)^2}$$ with ω the gyro-frequency and τ some time scale defined by scattering.

Re-writing Equation (1):

$$\langle \mathbf{v}_d \rangle = \frac{\beta P}{3} \left[f_s \nabla \times \frac{\mathbf{B}}{B_m^2} + \nabla f_s \times \frac{\mathbf{B}}{B_m^2} \right]$$ (2)

WS drifts modification can be accomplished through assuming:

CASE 1: $\omega\tau$ = constant (similar to Potgieter et al., 1989).

CASE 2: $\omega\tau$ ~ constant × P (see Burger et al., 2000).

CASE 3: $\omega\tau$ has spatial dependence (see Bieber & Matthaeus, 1997; Burger & Visser, 2010; Engelbrecht & Burger, 2015; Ngobeni & Potgieter, 2015).

CASE 2: The rigidity dependence

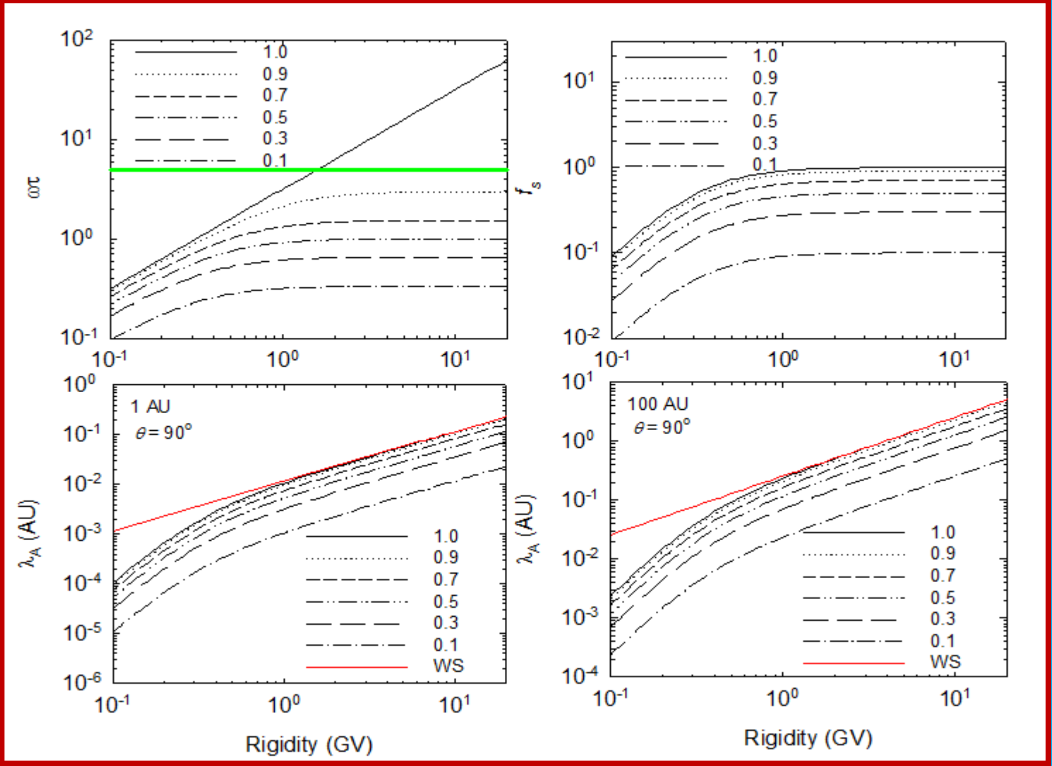
e.g. Ferreira, 2002; Potgieter & Vos, 2017 and etc

$$K_T = k_A \frac{\beta P}{3B_m} \frac{\left(P/P_0'\right)^2}{1+\left(P/P_0'\right)^2} \Rightarrow f_s = k_A \frac{\left(P/P_0'\right)^2}{1+\left(P/P_0'\right)^2}$$

then

$$\omega\tau = \sqrt{k_A \frac{\left(P/P_0'\right)^2}{1+\left(1-k_A\right)\left(P/P_0'\right)^2}}$$

for $k_A = 1.0$, $\omega\tau$ reduces to P/P_0' (assumption made by Burger et al. 2000)



Three important points

- When $k_{A0} < 1.0$ drifts are also reduced at $P > 1.0$ GV.
- For any value $\omega\tau > 5$, f_s remains ~ 1.0 (indicating no substantial drift reduction).
- WS drift scale ($\lambda_A = 3K_T/v$) is reduced by factor k_{A0} at $P > 1.0$ GV.

Extracting the spatial dependence of f_s

The analytical expression of the drift coefficient from Tautz and Shalchi is given as:

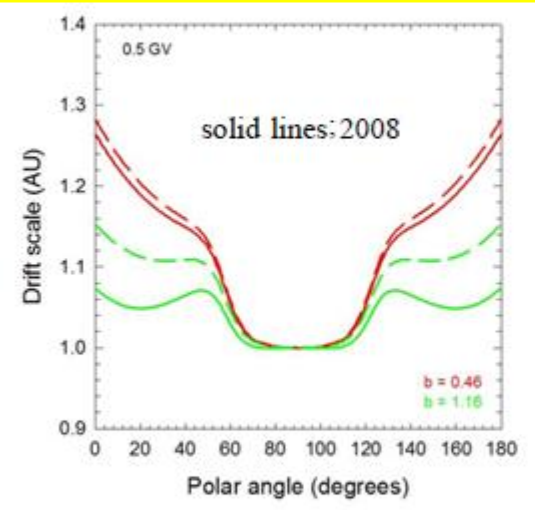
$$K_T = \frac{\beta P}{3B_m}\frac{1}{1+a\left[\frac{\delta B}{B_m}\right]^{2b}} = \frac{\beta P}{3B_m} f_s$$

$$f_s = \frac{1}{1+a\left[\frac{\delta B}{B_m}\right]^{2b}} = \frac{(\omega\tau)^2}{1+(\omega\tau)^2}$$

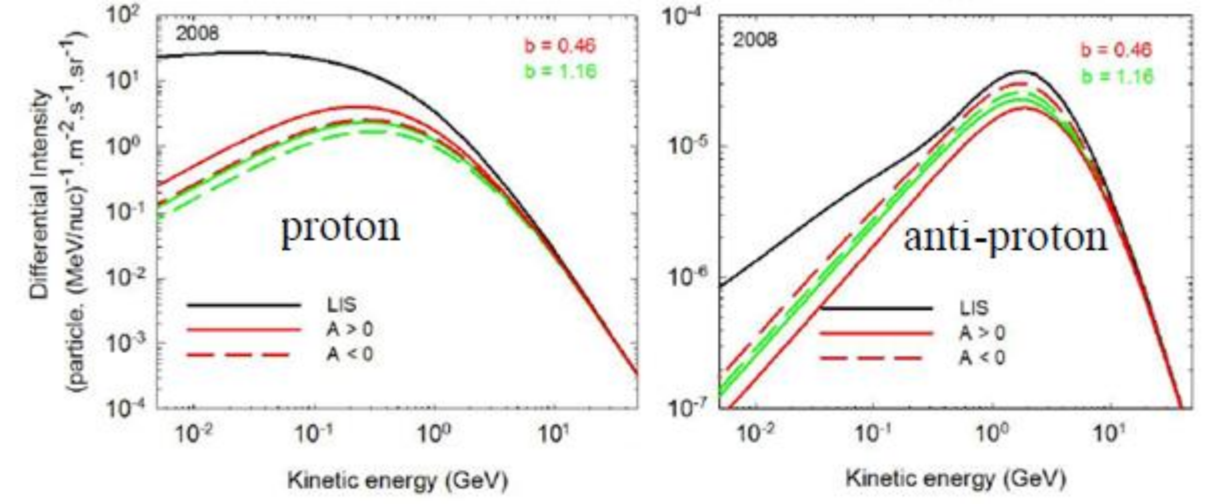
$$\omega\tau = \frac{1}{\sqrt{a}\left[\frac{\delta B}{B_m}\right]^{b}}$$

Best fit was achieved with $a = 1.09 \pm 0.52$ and $b = 0.81 \pm 0.35$

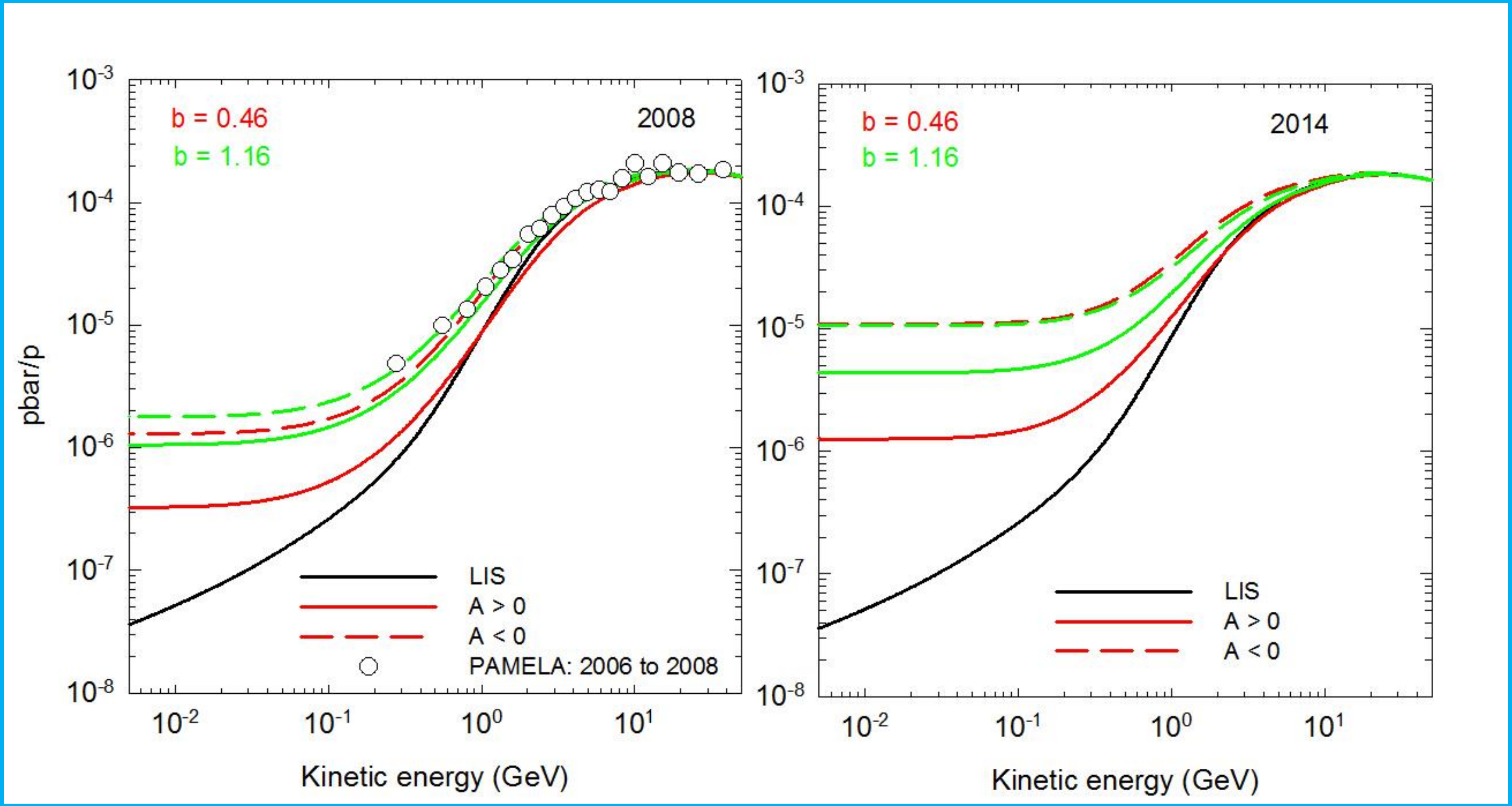
Normalized drift scale



Modeling results at the Earth: A > 0 and A < 0 comparison

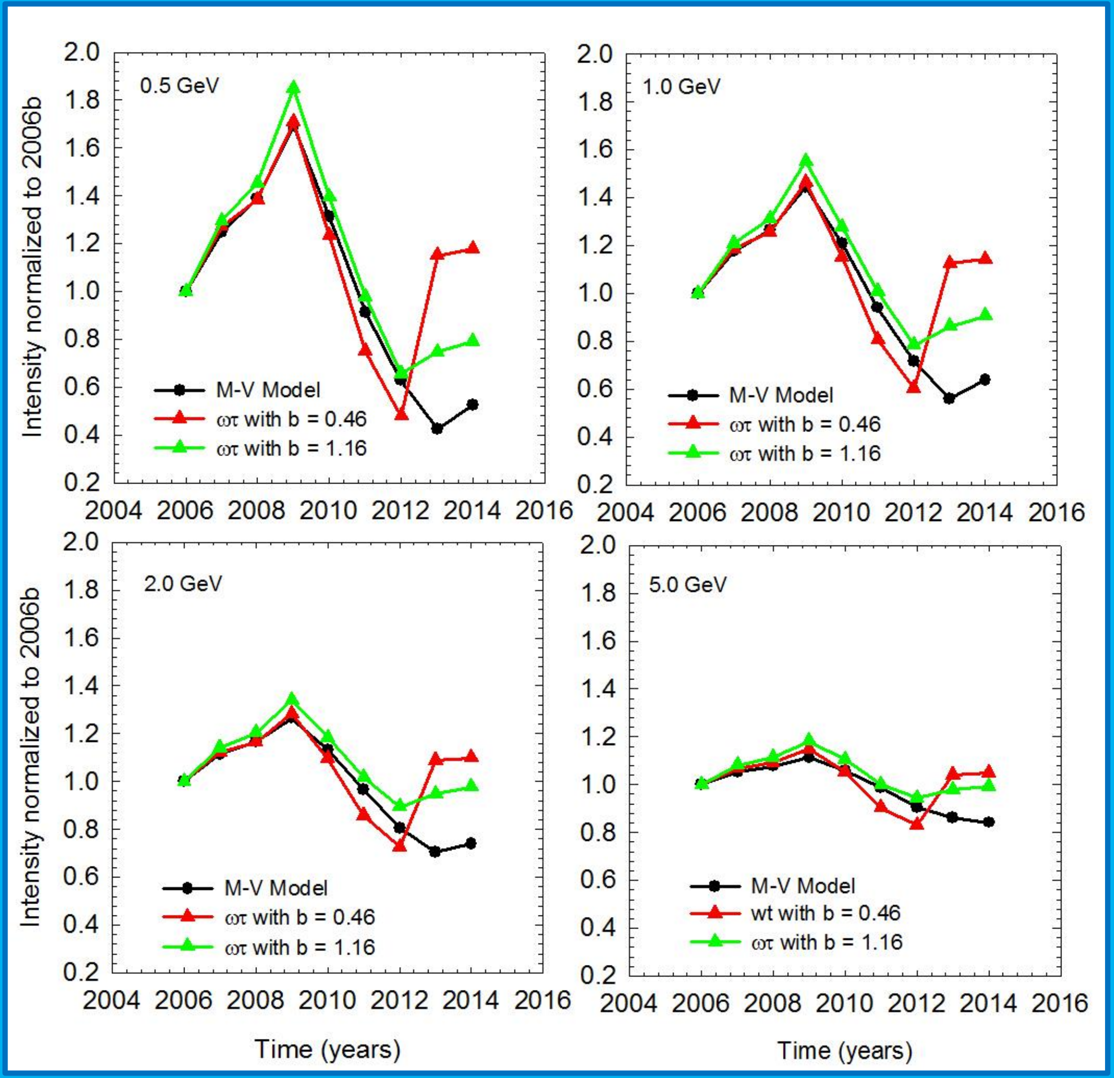


Energy dependence of anti-protons/protons ratios



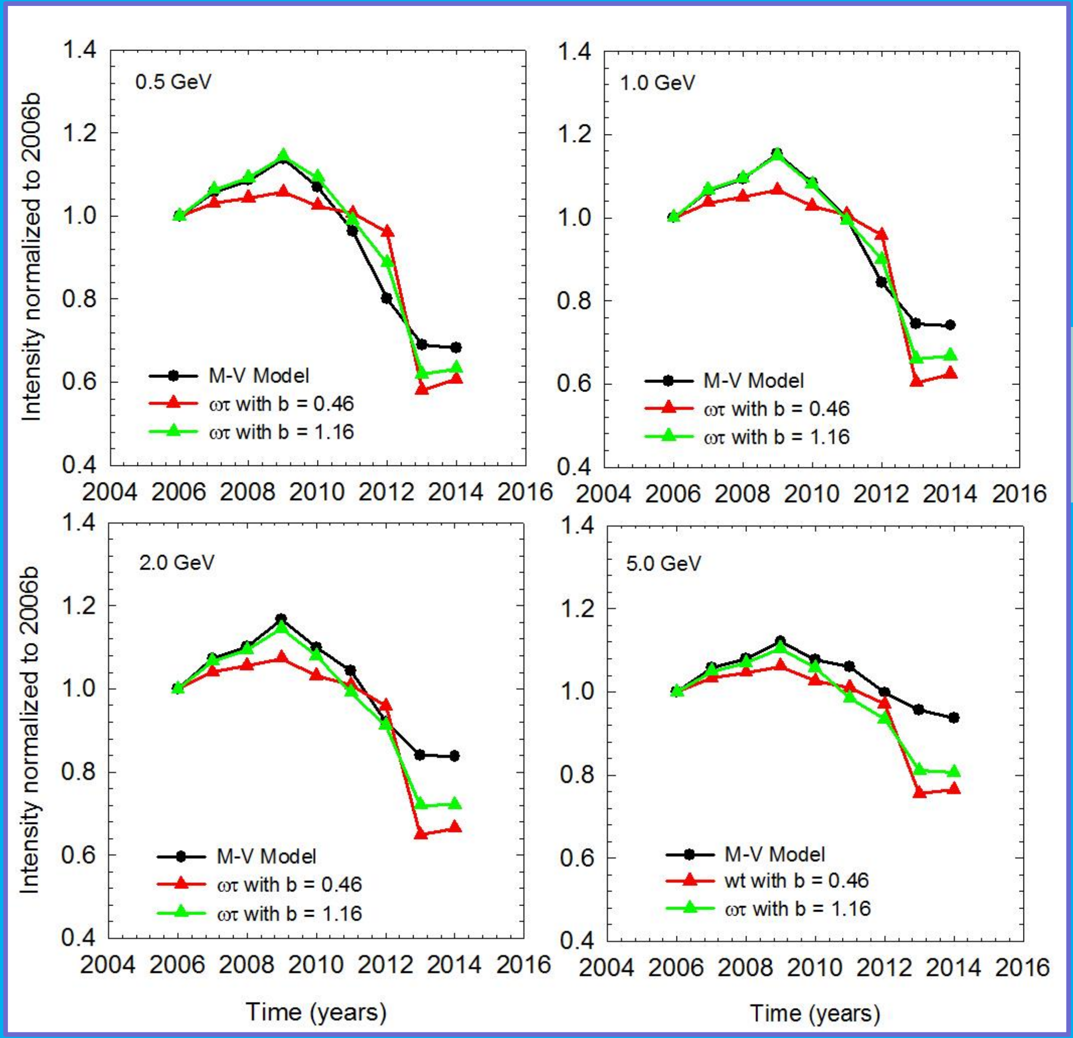
Effects of spatial dependence of ωτ are more prominent in the A > 0 cycle

Comparison between M-V Model and spatial dependence of ωτ: protons



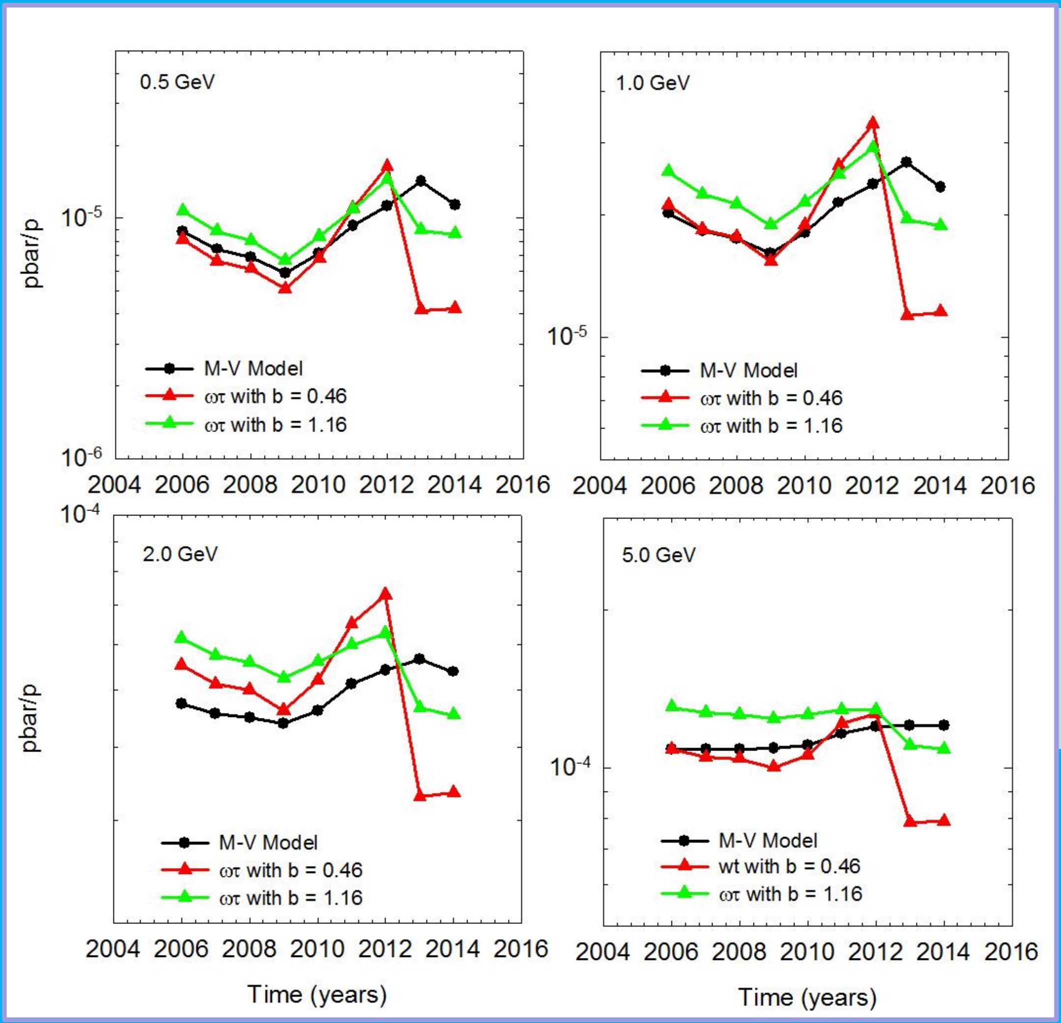
ωτ with b = 0.46 describes the M-V Model well from 2006 to 2010. While b = 1.16 gives better estimation of MV-Model between 2010 and 2012

Comparison between M-V Model and spatial dependence of ωτ: anti-protons



ωτ with b = 1.16 describes the M-V Model well from 2006 to 2012 below 5.0 GeV.

Modelling anti-proton to proton intensity ratios over time



- ✓ The proton intensity increased relatively more than anti-proton intensity until 2009 (corresponding to decreasing tilt angle).
- ✓ After 2009 (until 2012) proton intensity decreased relatively more (corresponding to increasing tilt angle).
- ✓ The large decreases in the ratio after 2012 is due to inadequate particle drift reduction and deviate largely with M-V Model.

Summary and Conclusions

- Using the self-consistent measurement validated 3D numerical model of Potgieter & Vos (2017) that includes particle drifts, the modulation of both protons and anti-protons was studied from 2006 to 2014 using.

- ✓ PAMELA proton observations together with numerical modeling confirmed that drifts played a significant role in modulation of GCRs from 2006 until around 2012.

- ✓ The intensity-time profile of protons from 2006 to 2012 can be qualitatively described with the assumed spatial dependence of $\omega\tau$, on the drift coefficient, by adjusting values of a and b.

- ✓ Both assumptions made about $\omega\tau$ are inadequate, and thus unsuitable, to describe pbar/p ratios between 2012 and 2014, as required by the MV-Model.