Spatial Gradients of Galactic Cosmic Ray Protons in the Inner Heliosphere

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PAMELA and Ulysses Observations

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Outline

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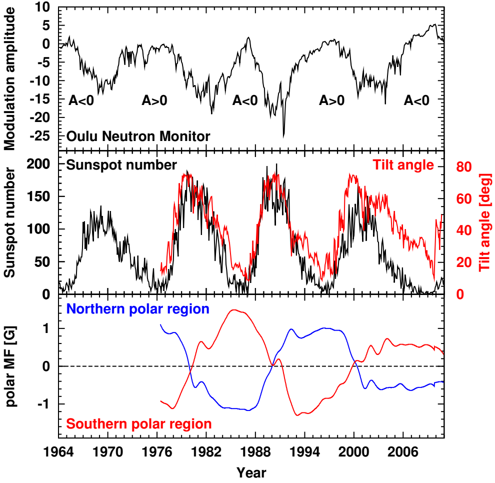
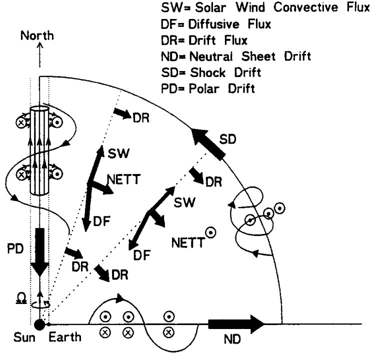
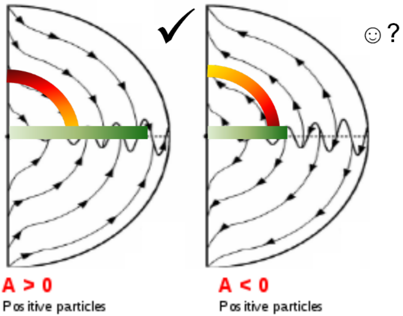
Introduction

Solar modulation of Galactic Cosmic Rays (GCR)



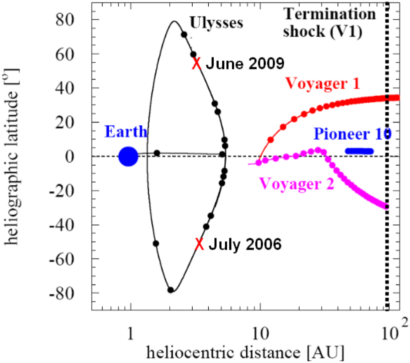


Expected behavior for A>0 and A<0-magnetic epoch



- Expected intensity variation wrt **radial** distance: Gradients always positive
- Expected intensity variation wrt **latitude**: Gradients positive or negative

Distribution of space probes



- IMP, ACE, Sampex, SOHO, STEREO, neutron monitors, and PAMELA (1 AU)
- Ulysses (1.3<R<5 AU, -80.2°<θ<80.2°)
- Voyager 1 (R>100 AU)
- Voyager 2 (R>80 AU)

Missions and instruments

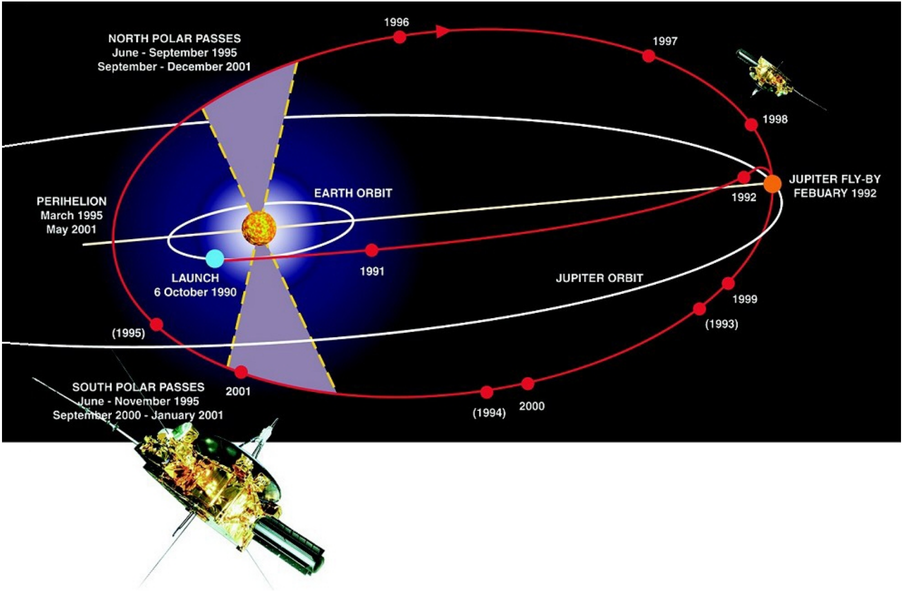
The PAMELA experiment

- PAMELA = Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics
- Satellite-borne apparatus designed to study charged particles, in particular antiparticles, in the cosmic radiation

Cosmic-ray particle	Energy range
Antiprotons	80 MeV–190 GeV
Positrons	50 MeV–270 GeV
Electrons	50 MeV–400 GeV
Protons	80 MeV–700 GeV
Electrons + positrons	up to 2 TeV
Light nuclei (up to $Z = 6$)	100 MeV/n–250 GeV/n
Antinuclei	Sensitivity 95% CL
Antihelium/helium ratio	of the order of 10^{-7}

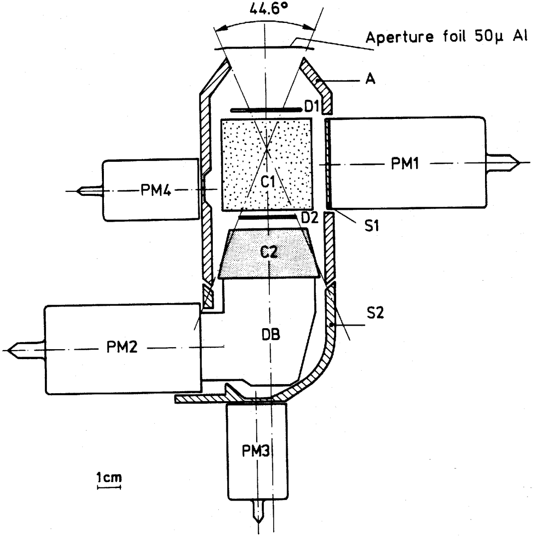
- Built by the Wizard collaboration (RUS, IT, GER and SWE)
- Launched on 15 June 2006 at Bajkonur
- Polar elliptical orbit, inclination 70.0°, altitude 350-610 km
- Height ∼1.3 m, total mass 470 kg

The Ulysses mission



Kiel Electron Telescope (KET)

- D1, D2:
  semiconductor detectors
  (0.5mm)
- C1, C2:
  Cerenkov detectors
  (aerogel/lead)
- S1, S2:
  plastic scintillation
  detectors
- PM1 - PM4:
  photomultiplier
- A:
  anticoincidence
  (plastic scintillator)



Coincidence channels

Name	Logic	primary particles	energy range (MeV/N)	Response[1]-factor (cm^2 sr MeV/N)	sectors
K1 (P1)	D11 $\overline{\text{D12 C10 D20 C20 S20 A0}}$	p	2.7-5.4	17.6	—
		p	23.1-34.1	71.5	
		He	2.3-2.7	2.6	
K21-K28 (P4)	D12 $\overline{\text{D13 C10 D20 C20 S20 A0}}$	p	5.4-23.1	115	8
		He	2.7-6.0	15	
		He	20.4-34.2	89.7	
K3 (P32)	D11 D20 $\overline{\text{D12 C10 C20 S20 A0}}$	p	34-125	70^d	—
K34 (P116)	D10 D20 S20 $\overline{\text{D12 C10 C20 A0}}$	p (F)	125-250	+	—
		p (B)	160-260	152^d	—
		He	126-190		
K12 (P190)	D10 D20 S20 C20 $\overline{\text{D11 C10 D21 C21 A0}}$	p	250-2200	3300	—
K10 (P4000)	D10 C10 D20 S20 C20 $\overline{\text{D11 C11 D21 C21 A0}}$	p	>2200	*I*	—
K2 (A4)	D13 $\overline{\text{C10 D20 C20 S20 A0}}$	He	5.4-23.1	115	—
K33 (A32)	D12 D21 $\overline{\text{D13 C10 C20 S20 A0}}$	He	34-125	70.0^d	—
K29 (A116)	D12 D21 S20 $\overline{\text{D13 C10 C20 A0}}$	He (F)	125-155	+	—
		He (B)	155-225	88	—
K31 (A190)	D11 D21 S20 C20 $\overline{\text{D12 C10 A0}}$	He	250-2100	3200	—
K30 (A4000)	D11 C10 D21 S20 C20 $\overline{\text{D12 C11 C21 A0}}$	He	>2100	*I*	—
K13-20 (E4)	D10 C10 D20 $\overline{\text{D11 C11 C20 S20 A0}}$	e	4-9	*tbd*	8
K11 (E12)	D10 C10 D20 C20 $\overline{\text{D11 C11 D21 S20 A0}}$	e	9-500	*tbd*	—
K32 (E300)	D10 C10 D20 C21 S20 $\overline{\text{D11 C11 D21 A0+A1}}$	e	>500	*tbd*	—

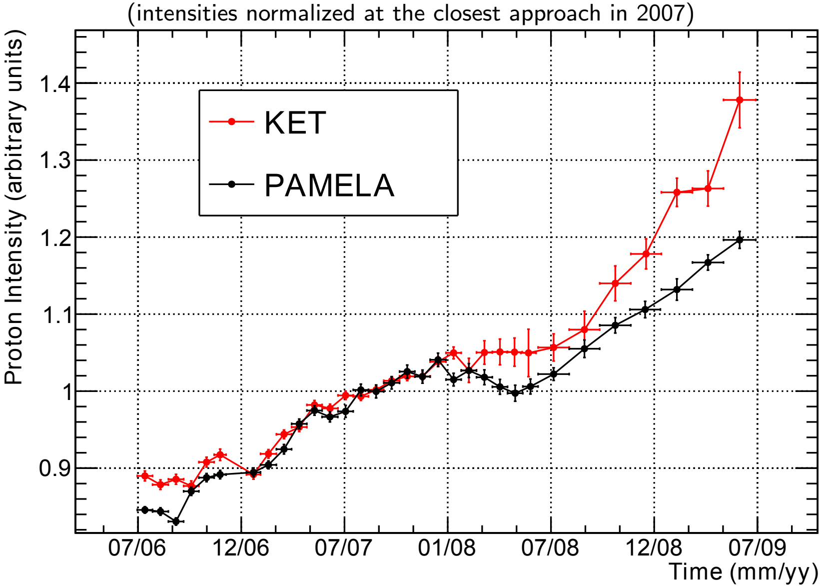
Calculation of the gradients

Calculation of the gradients

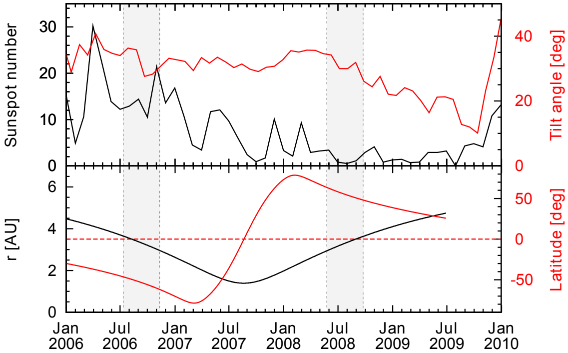
- Assume that temporal and spatial variations can be separated
- $J_U(R, t, r, \theta)$ - intensity at Ulysses (r, θ) at time t and rigidity R
- $J_E(R, t, r_E, \theta_E)$ - intensity measured by PAMELA at Earth
- $G_r(R)$ - radial gradient
- $G_\theta(R)$ - latitudinal gradient
- $\Delta r = r_U - r_E$ - radial distance
- $\Delta\theta = |\theta_U| - |\theta_E|$ - latitudinal distance *(assume symmetric distr.)*

$$
\begin{aligned}
J_U &= J_E \cdot \exp\left(G_r \cdot \Delta r\right) \cdot \exp\left(G_\theta \cdot \Delta\theta\right) \\
\Rightarrow \quad \ln\left[\frac{J_U}{J_E}\right] &= G_r \cdot \Delta r + G_\theta \cdot \Delta\theta \\
\Rightarrow \quad \frac{1}{\Delta r}\ln\left[\frac{J_U}{J_E}\right] &= G_r + G_\theta \cdot \frac{\Delta\theta}{\Delta r}
\end{aligned}
$$

Intensity profile (∼1.7 GV protons)



Temporal variation

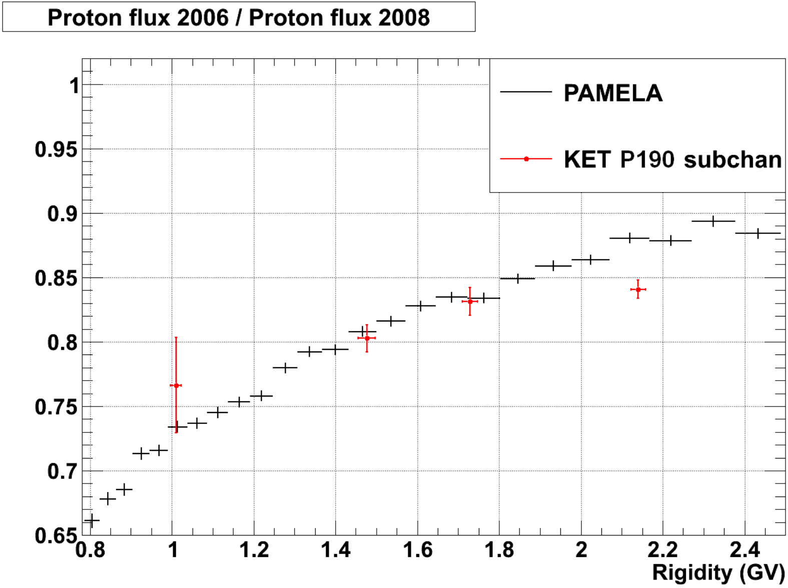


- t_1,t_2: Ulysses at comparable position in southern and northern hemisphere
- Assume that the gradients are the same for both periods

$$J_U = J_E \cdot \exp\left(G_r \cdot \Delta r\right) \cdot \exp\left(G_\theta \cdot \Delta\theta\right)$$

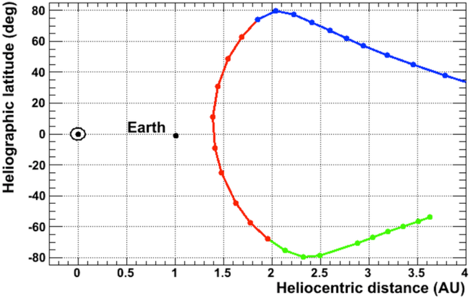
$$\Rightarrow \quad \frac{J_{\mathrm{U}}(R, t_1, r_1, \theta_1)}{J_{\mathrm{U}}(R, t_2, r_2, \theta_2)} = \frac{J_{\mathrm{E}}(R, t_1, r_E, \theta_E)}{J_{\mathrm{E}}(R, t_2, r_E, \theta_E)}$$

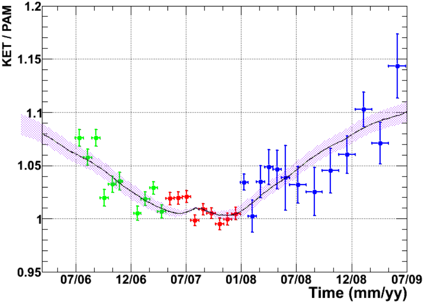
Temporal variation



Calculation of the gradients (∼1.7 GV protons)

(intensities normalized at the closest approach in 2007)

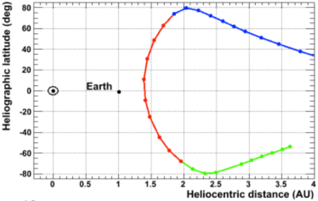


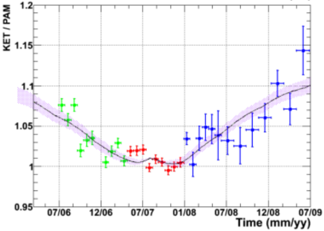


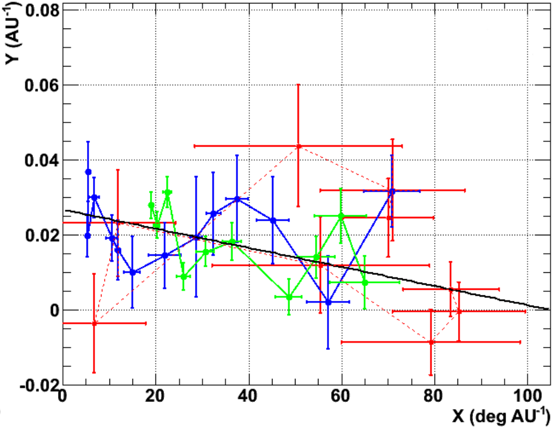
$$\underbrace{\frac{1}{\Delta r} \ln\left[\frac{J_U}{J_E}\right]}_{=:Y} = G_r + G_\theta \cdot \underbrace{\frac{\Delta\theta}{\Delta r}}_{=:X}$$

$$Y = G_r + G_\theta \cdot X$$

Calculation of the gradients (∼1.7 GV protons)

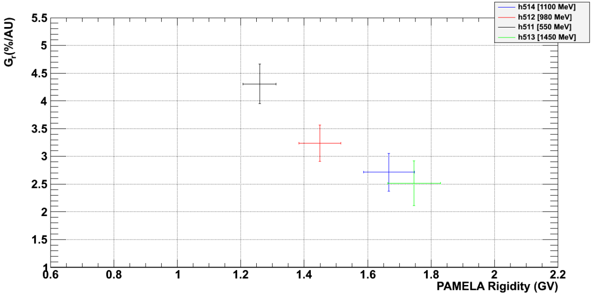


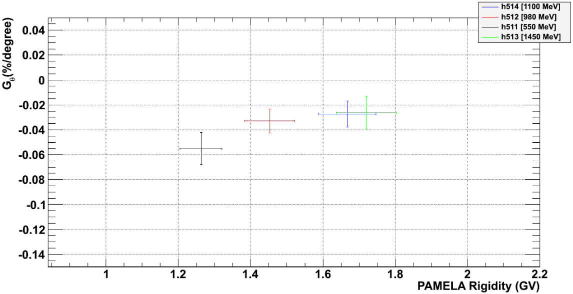




$$
\begin{aligned}
Y &= G_r + G_\theta \cdot X \\
G_r &= (2.7 \pm 0.2)\%/\mathrm{AU} \\
G_\theta &= (-0.024 \pm 0.005)\%/\mathrm{degree} \\
\chi^2/ndf &= 1.9
\end{aligned}
$$

Calculation of the gradients

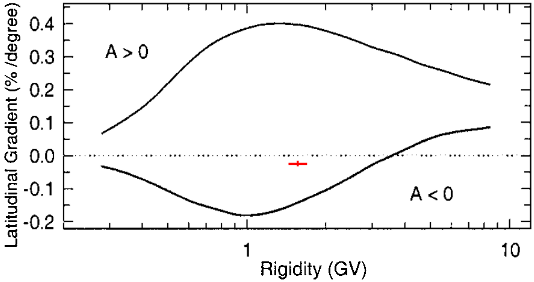




Summary

Summary

- Investigation period: July 2006 - July 2009 (A<0)
- Proton rigidities: $\sim$ 1.2 - 1.8 GV
- Radial gradients:
  - Within expectations
- Latitudinal gradients:
  - Correct trend (G_θ<0) but probably too big



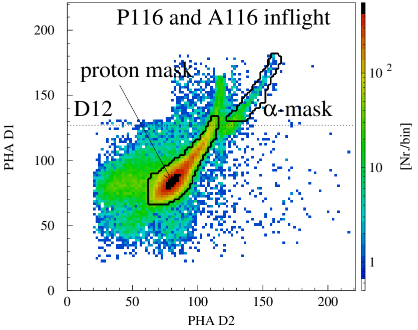
Work in progress

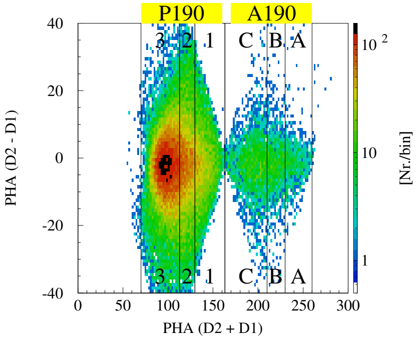
Pulse Height Analysis (PHA)

- Energy loss ϵ in semiconductor detectors (D1, D2) and number of photons in light detectors (C1, C2, S2) are transmitted (for a statistical amount of measured particles)
- Calculate from them the *pulse height numbers*:

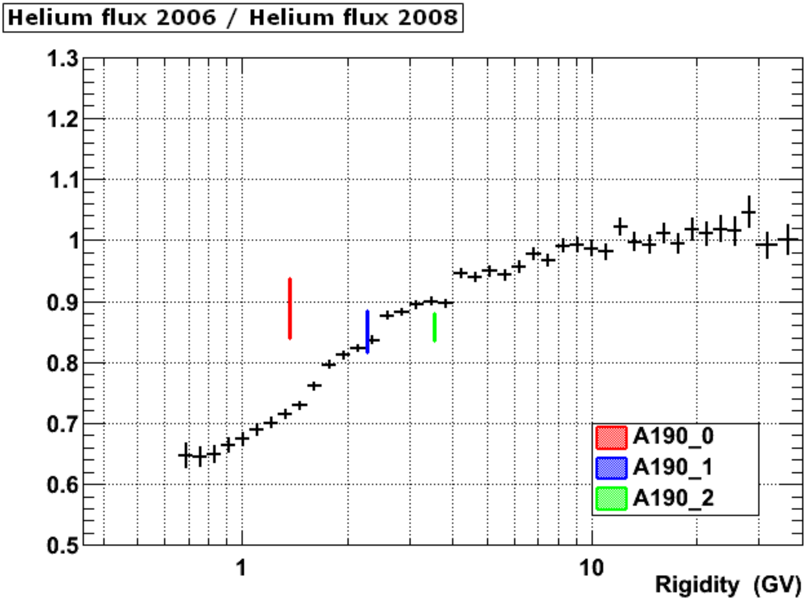
$$n = \frac{\log(A \cdot \epsilon) - B}{C}$$

(A, B, and C are detector and electronic specific constants)



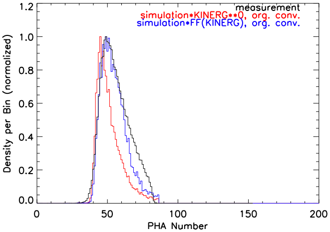


Helium



Helium flux 2006 / Helium flux 2008
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
1
10
Rigidity (GV)
A190_0
A190_1
A190_2

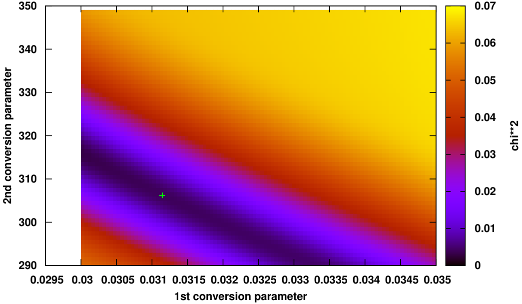
Redefining PHA-energy conversion



- Take quiet time measurements and GEANT3 simulation
- Fold simulation (E^0) with corresponding forcefield spectrum
- Calculate χ^2 as qualitative difference between both curves
- Run over set of conversion parameters and minimize χ^2

Redefining PHA-energy conversion

D1:



D2: