Latitudinal and radial gradients of galactic cosmic ray protons in the inner heliosphere
PAMELA and Ulysses observations

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Distribution of space probes

- **1 AU**: IMP, ACE, Sampex, SOHO, STEREO, neutron monitors, and PAMELA
- **Ulysses**: $1.3 \text{ AU} < r < 5 \text{ AU}$, $80.2^\circ < \theta < 80.2^\circ$
- **Voyager 1**: $r > 110 \text{ AU}$
- **Voyager 2**: $r > 90 \text{ AU}$

X July 2006
X June 2009

heliocentric distance [AU]
Expected intensity contours for the $A>0$ and $A<0$-magnetic epoch (Protons)

- Expected intensity variation vs distance: Gradients always positive
- Expected intensity variation vs latitude: Gradients positive and negative
Determination of gradients

- $G_R = \text{radial gradient}$
- $G_\theta = \text{latitudinal gradient}$
- $R, \theta = \text{radial distance and absolute value of latitude}$
- $I(t,R,\theta) = \text{Intensity at Ulysses position}$
- $I_{PAM}(t) = I(t, R \approx 1 \text{AU}, \theta \approx 0^\circ) = \text{Intensity at the position of Pamela}$

\[
\frac{I_{KET}(t, R, \theta)}{I_{PAM}(t)} = e^{G_R \Delta R} e^{G_\theta \Delta \theta}
\]
**Importance of gradients - vanishing latitudinal gradient**

\[ \frac{I_{KET}(t, R, \theta)}{I_{PAM}(t)} = e^{G_R \Delta R} \]

- The expected variation reflects the movement of Ulysses with radial distance.

- Period 1 and period 3 can be well described by such a variation

- Period 2 however disagrees with the prediction → latitudinal gradient is not zero
Importance of gradients - vanishing radial gradient

from 1.5 to 1.6 GV

\[
\frac{I_{KET}(t, R, \theta)}{I_{PAM}(t)} = e^{G_\theta \Delta \theta}
\]

- The expected variation reflects the movement of Ulysses with latitudinal distance.

  - Period 1 and period 3 can be well described by such a variation

  - Period 2 however disagrees with the prediction → radial gradient is not zero
Importance of gradients - the right combination

- The right combination of radial and latitudinal gradients will reflect all three periods:

$$\frac{I_{KET}(t)}{I_{PAM}(t)} = e^{G_R \Delta R} e^{G_\theta \Delta \theta}$$
Determination of gradients

\[ \frac{I_{KET}(t)}{I_{PAM}(t)} = e^{G_R \Delta R} e^{G_\theta \Delta \theta} \]

\[ \frac{1}{\Delta R} \ln \left( \frac{I_{KET}}{I_{PAM}} \right) = G_R + G_\theta \left( \frac{\Delta \theta}{\Delta R} \right) \]

\[ Y = G_R + G_\theta \quad X \]
Ulysses orbit

from 1.5 to 1.57069 GV
Ulysses orbit

Heliocentric distance (AU)

Heliographic latitude (deg)

Earth

Ulysses

from 1.5 to 1.57069 GV
Ulysses orbit

Heliocentric distance (AU)

Y (AU\(^{-1}\))

X (deg / AU)

from 1.5 to 1.57069 GV
Ulysses orbit

from 1.5 to 1.57069 GV
Ulysses orbit

from 1.5 to 1.57069 GV
Ulysses orbit

from 1.5 to 1.57069 GV

Heliocentric distance (AU)

Y (AU⁻¹)

X (deg / AU)
Ulysses orbit

Heliocentric distance (AU)

Y (AU\(^{-1}\))

X (deg / AU)

from 1.5 to 1.57069 GV
Ulysses orbit

Heliocentric distance (AU)

Y (AU\(^{-1}\))

X (deg / AU)

from 1.5 to 1.57069 GV
Ulysses orbit

from 1.5 to 1.57069 GV

Heliocentric distance (AU)

Heliographic latitude (deg)

Earth

Ulysses
Ulysses orbit

from 1.5 to 1.57069 GV
Ulysses orbit

from 1.5 to 1.57069 GV
Ulysses orbit

from 1.5 to 1.57069 GV

Heliocentric distance (AU) vs. Heliographic latitude (deg)

Y (AU^{-1}) vs. X (deg / AU)
Ulysses orbit

Heliocentric distance (AU)

Y (AU⁻¹)

from 1.5 to 1.57069 GV

Earth
Ulysses orbit

from 1.5 to 1.57069 GV
Ulysses orbit

from 1.5 to 1.57069 GV

Heliocentric distance (AU)

Earth

Ulysses

Y (AU^-1)
Ulysses orbit from 1.5 to 1.57069 GV
Ulysses orbit

Heliocentric distance (AU)

Earth

Ulysses

from 1.5 to 1.57069 GV

$G_R = (\pm) \%/AU$

$G_\theta = (\pm) \%/^\circ$

$\chi^2/ndf =$
\[ \frac{I_{KET}}{I_{PAM}} = e^{G_R \Delta R} \cdot e^{G_\theta \Delta \theta} \]

\[ G_R = (3.9 \pm 0.2) \% \]

\[ G_\theta = (-0.051 \pm 0.007) \% \]

\[ \chi^2/\text{ndf} = 1.6 \]
Summary and Outlook

• Radial and latitudinal gradients for protons between 1.2 and 1.8 GV, in A<0 solar magnetic epoch, established and consistent with previous measurements.

• The combination of PAMELA and Ulysses will allow precision studies of the gradients at different energies.
Particle Gradient (AU$^{-1}$) vs. Year

- 1.2 GV
- 1.7 GV
- 2.5 GV

Square Symbols – Positive Charged
Circle Symbols – Negative Charged
Energy choice: PAMELA energy > KET energy

Protons / (cm$^2$ sr s GeV)

KET / PAM

Time

from 3.13394 to 3.28164 GV
Energy choice: PAMELA energy < KET energy

Protons / (cm$^2$ sr s GeV)

KET / PAM

Time

from 0.824311 to 0.86316 GV
Energy choice: PAMELA energy = KET energy

Protons / (cm$^2$ sr s GeV)

KET / PAM

Time

from 1.5 to 1.57069 GV
from 1.5 to 1.6 GV

![Graph showing proton flux from 1.5 to 1.6 GV]
1. Period: Radial distance decreases and heliographic latitude increases but intensity ratio decreases.
1. Period: Radial distance decreases and heliographic latitude increases but Intensity ratio decreases.

2. Period: Absolute value of latitude decreases, while radial distance first decreases and then increases. Intensity ratio is constant.
1. Period: Radial distance decreases and heliographic latitude increases but Intensity ratio decreases

2. Period: Absolute value of latitude increases, while radial distance first increases and then decreases. Intensity ratio is constant

3. Period: Radial distance increases and heliographic latitude decreases but Intensity ratio increases
from 1.5 to 1.57069 GV

\[ G_R = (3.9 \pm 0.2) \% / \text{AU} \]

\[ G_\theta = (-0.051 \pm 0.007) \% / \text{deg} \]

\[ \chi^2 / \text{ndf} = 1.6 \]
from 1.64472 to 1.72223 GV

\[ G_R = (3.1 \pm 0.2) \% / \text{AU} \]
\[ G_\theta = (-0.050 \pm 0.006) \% / \text{deg} \]
\[ \chi^2/\text{ndf} = 2.1 \]
from 1.8034 to 1.88839 GV

\[ G_R = (2.6 \pm 0.2) \% / \text{AU} \]

\[ G_\beta = (-0.054 \pm 0.006) \% / \text{deg} \]

\[ \chi^2/\text{ndf} = 3.3 \]
from 1.43249 to 1.5 GV

\[ G_R = (3.8 \pm 0.2) \% / \text{AU} \]

\[ G_\theta = (-0.056 \pm 0.007) \% / \text{deg} \]

\[ \chi^2/\text{ndf} = 2.7 \]
from 1.36802 to 1.43249 GV

\[ G_R = (4.4 \pm 0.2) \% / \text{AU} \]
\[ G_\theta = (-0.071 \pm 0.007) \% / \text{deg} \]
\[ \chi^2/\text{ndf} = 3.5 \]
from 1.13787 to 1.19149 GV

\[ G_{R} = (5.6 \pm 0.3) \% \text{ AU}^{-1} \]
\[ G_{\phi} = (-0.092 \pm 0.009) \% \text{ deg}^{-1} \]
\[ \chi^{2}/ndf = 6.0 \]
Parkers transport model

\[ \frac{\partial f}{\partial t} = \nabla \cdot \left( \kappa^{(S)} \cdot \nabla f \right) \quad \text{diffusion} \]

\[ - \vec{V} \cdot \nabla f \quad \text{convection} \]

\[ - \vec{v}_D \cdot \nabla f \quad \text{drift} \]

\[ + \frac{1}{3} \left( \nabla \cdot \vec{V} \right) \frac{\partial f}{\partial \ln \rho} \quad \text{ad. energy change} \]

\[ + Q \quad \text{Source term} \]

\( f \) is the differential CR number density with respect to \( \rho \):
Propagation parameters

- Solving the equation and comparing to measurements we will learn about:
  1. Diffusion coefficients
  2. Drift effects in the heliospheric magnetic field
The three dimensional heliosphere - Ulysses trajectory
A detailed view on the Ulysses trajectory from July 1996 to the end of 2008

- July 2006: Ulysses was at 3.7 AU and ~55° South
- August 2007: Ecliptic crossing at a distance of about 1.4 AU
- Closest approach: at about 1.39 AU and 7° North
- December 2008: 4.0 AU and 32° North
• KET protons vs time
  PAMELA protons vs time

• KET/PAMELA vs time

• R vs time

• | lat | vs time
Importance of gradients - vanishing latitudinal gradient

1. The expected variation reflects the movement of Ulysses with radial distance.
2. Period 1 and 3 can be described by such a variation.
3. Period 2 however disagrees with the prediction.
4. Latitudinal gradient is not zero.
Importance of gradients - vanishing radial gradient

1. The expected variation with a negative latitudinal gradient does not reflect the measurements by Ulysses
2. Period 1 and 3 can be described by such a variation
3. Period 2 however disagrees with the prediction
4. Radial gradient is not zero
Importance of gradients - the right combination

- The right combination of radial and latitudinal gradients will reflect all three periods
- KET and Pamela measurements of the intensity time profile agree very well.
- First determination of the latitudinal gradient in the inner heliosphere by
Outline

• What kind of observations are available before Pamela?
• What do we want to achieve?
• The radial and latitudinal gradient from Pamela and Ulysses at \( \sim 2 \) GV for protons!
1. Period: Radial distance and heliographic latitude decreases and increases but intensity ratio decreases.

2. Period: Absolute value of latitude increases, while radial distance first increases and then decreases. Intensity ratio is constant.

3. Period: Radial distance and heliographic latitude decreases but intensity ratio increases.