Solar modulation of Galactic Cosmic Rays

Fernando Barao

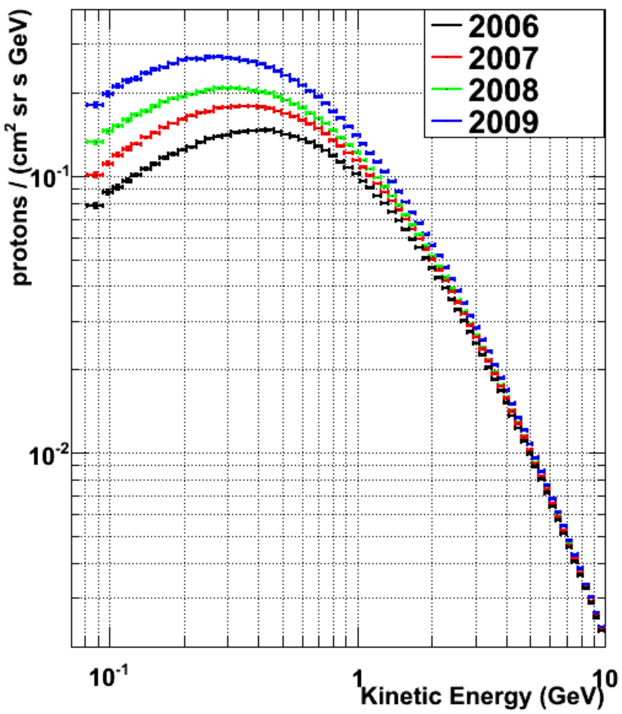
IST/LIP (on leave at LAPP)

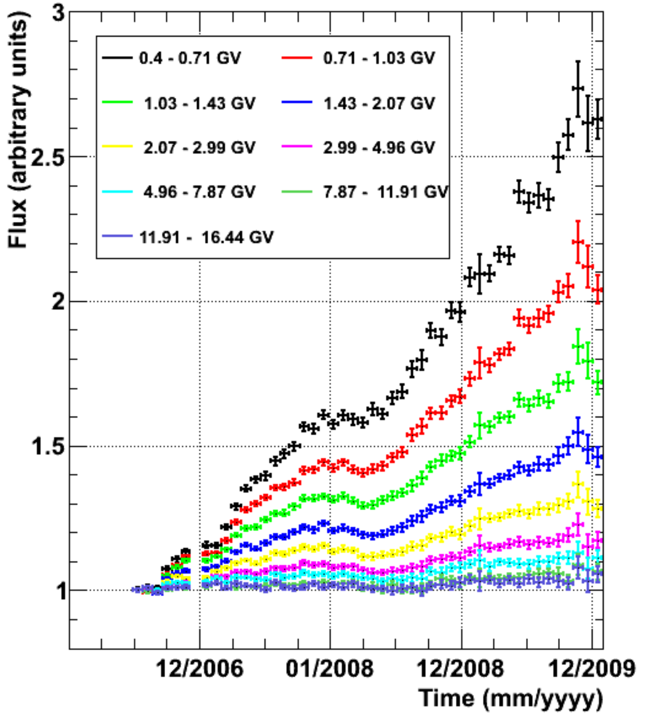
Outline

- Sun environment : heliosphere, magnetic field
- Solar activity monitoring
- Solar flares
- Modulation of Cosmic Rays
  - Parker equation
  - Force-field approximation
  - 1D vs Force-field
- Prospects

Cosmic rays : solar modulation

PAMELA measurements of protons fluxes
between 2006 and 2009

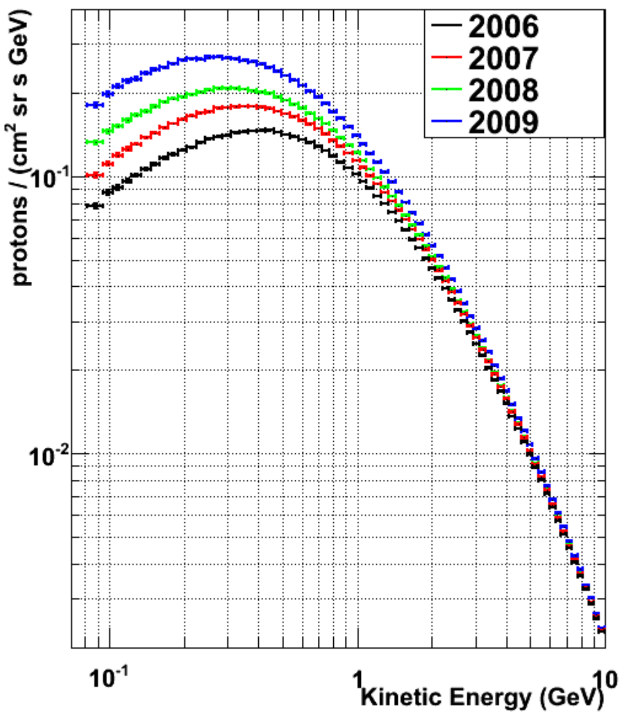


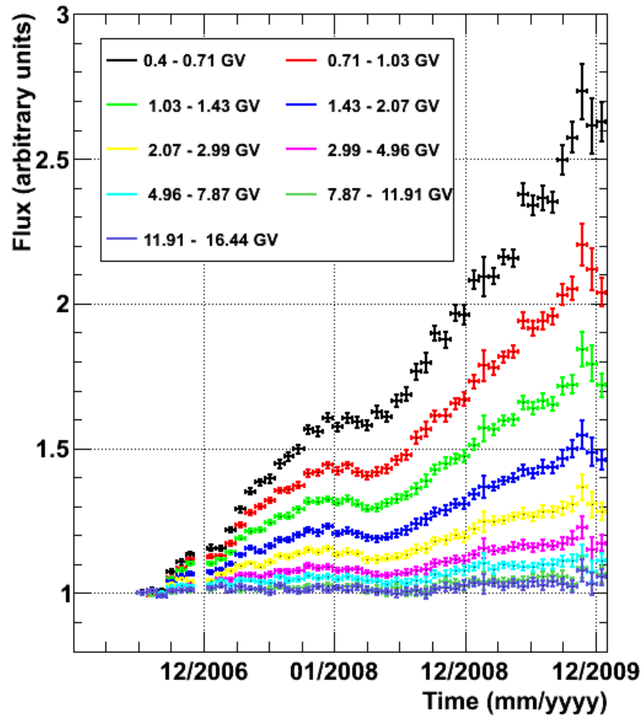


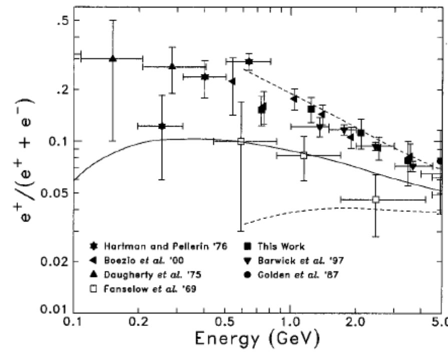
**a decrease on the proton fluxes,
specially at low energies, is observed**

Cosmic rays : solar modulation

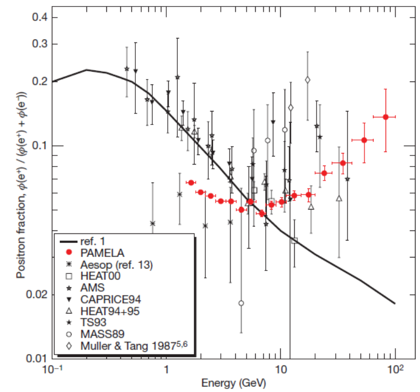
PAMELA measurements of protons fluxes
between 2006 and 2009







Clem et al. JGR 105 (2000)



a decrease on the proton fluxes, specially at low energies, is observed

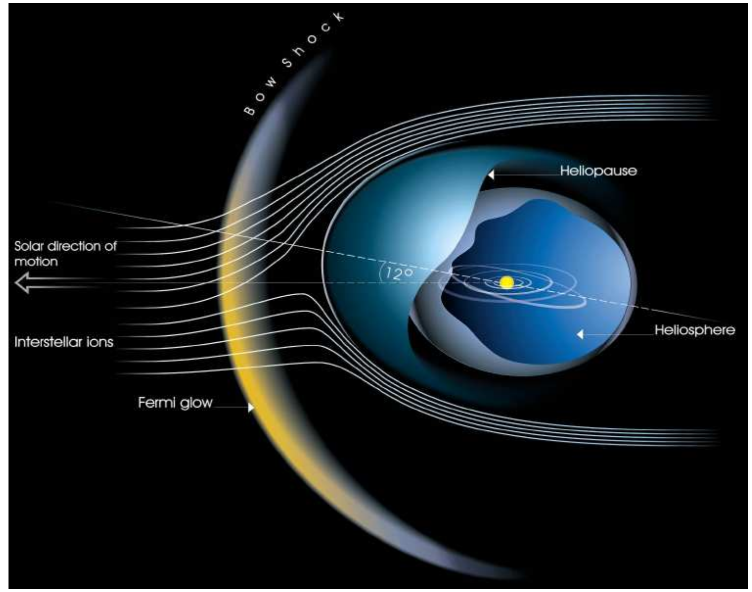
Charge sign dependence...

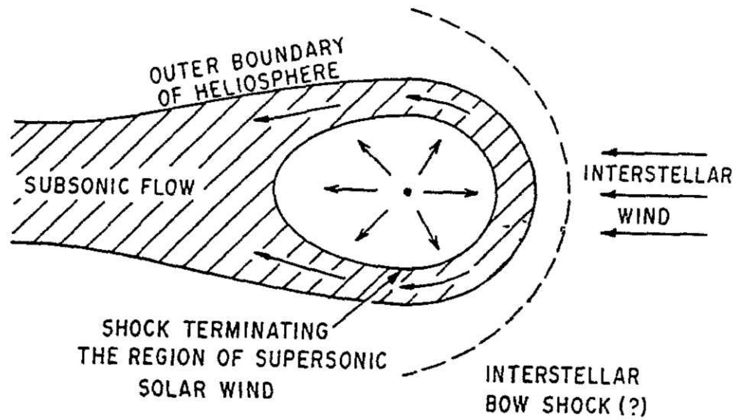
Sun activity

solar wind, magnetic field, flares

Heliosphere

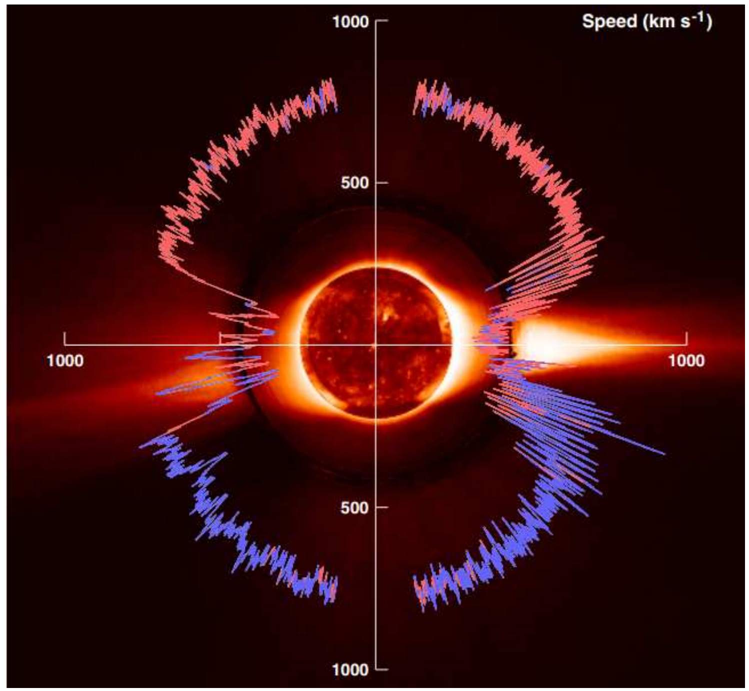
- ✔ A region of space influenced by the sun and its expanding **Corona** : solar wind
  - ► *size : 100-150 AU*
- ✔ A magnetic cavity in the interstellar wind influenced by :
  - ► solar wind
  - ► solar magnetic field
- ✔ The heliospheric Termination Shock (TS) and heliosheath are the interfaces of the heliosphere with the surrounding interstellar medium
- ✔ Voyager 1,2 are currently exploring the heliosheath (between TS and heliopause)





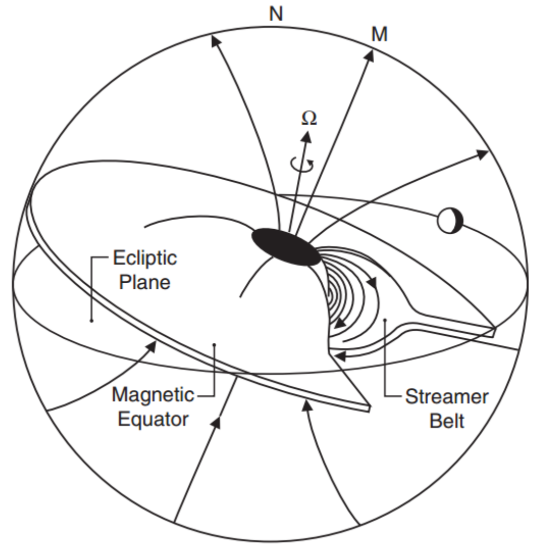
Solar wind

- ✔ A continuous flow of charged particles from SUN with velocities around 400 Km/s
  - ▶ mainly composed of electrons and protons
  - ▶ flux $\sim 10^{12}$ particles/$m^2.s$
  - ▶ first continuous observation made by Marina 2 spacecraft (1962)
  - ▶ detailed measured by the spacecraft Ulysses (three orbits)
- ✔ At solar minimum (1995) solar wind faster on poles than in equator obs (fig)
- ✔ Around 4 days to reach Earth (1 AU)
- ✔ Carries the sun magnetic field to the interplanetary space

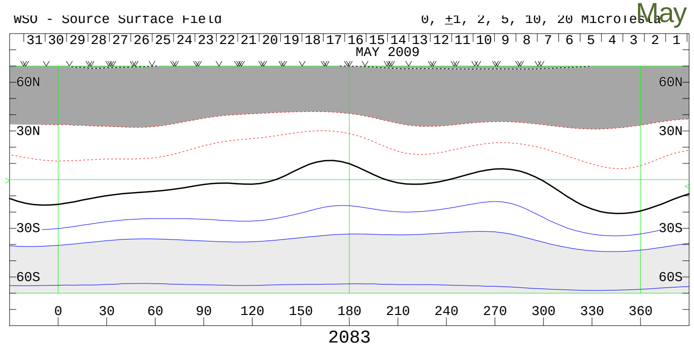


Solar magnetic field

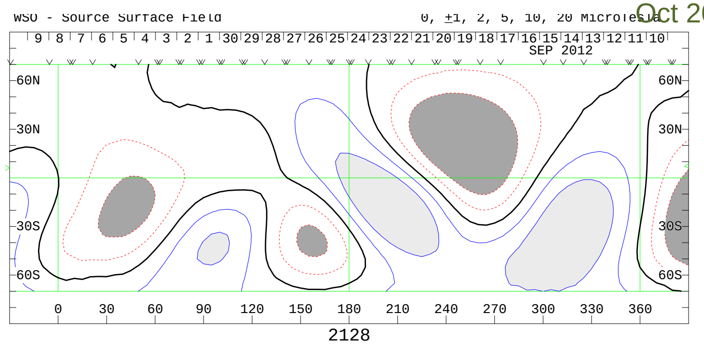
- ✔ The SUN rotates with a period of $\simeq 27.27$ days (Carrington rotation - started on Nov 9, 1853)
- ✔ The magnetic field at the solar magnetic poles approximates that of a dipole
- ✔ Theres exist a progressive offset between the SUN magnetic and rotational axes as the SUN activity goes from minimum to maximum
  - ▶ near solar maximum the magnetic field assumes a much more complicated structure
- ✔ There exist a a reversal of the magnetic field polarity every 11 years at solar maximum
  - ▶ **polarity** $+$, field lines going away from SUN



May 2009



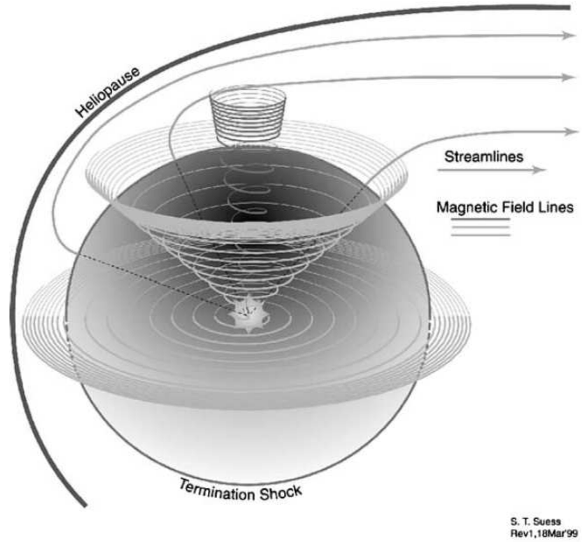
Oct 2012



The archimedian spiral

✔ very high electric conductivity of the solar wind plasma carries SUN magnetic field into the heliosphere

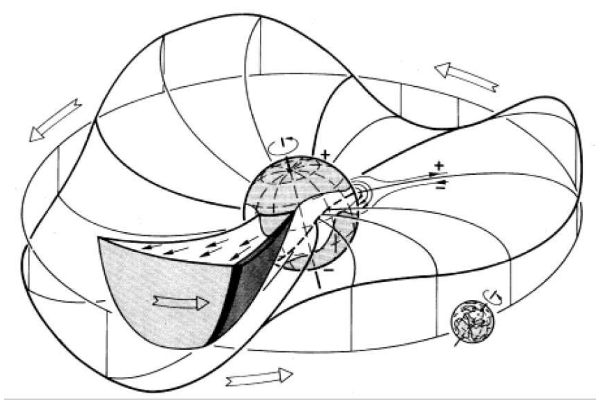
- ▶ $B \sim$ nT
- ▶ SUN rotation gives the magnetic field the form of an Archimedian spiral (Parker spiral)



$$\vec{B} = \frac{B_0}{r^2}\left[\vec{e}_r - \frac{\Omega(r - r_A)}{V}\cos\theta\vec{e}_\phi\right]\left[1 - 2H(\theta - \theta')\right]$$

✔ There exist a magnetically neutral layer (heliospheric current sheet) that separates the large-scale regions of opposite magnetic polarity

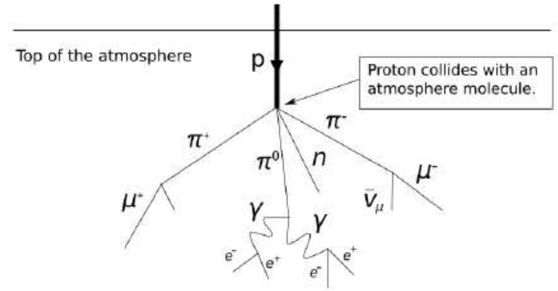
- ▶ flat and coincident with heliospheric equator at solar minimum
- ▶ warped with a tilt angle (offset between axes) as the SUN activity increases

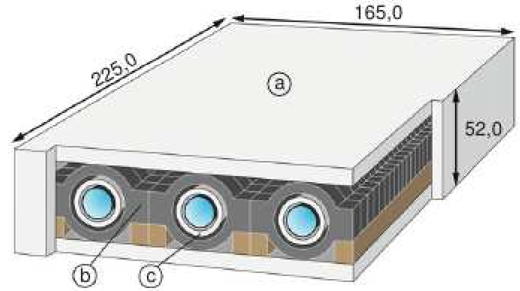


Solar activity indicators

Neutron monitors

- ✔ primary cosmic rays (protons) interact with the atmosphere and produce secondary neutrons
- ✔ the neutron component is measured by neutron monitors at different geographical altitudes and latitudes
  different geomagnetic cutoffs
- ✔ detection by proportional tubes surrounded respectively by high-Z (lead) and low-Z (polyethylene) materials to amplify secondary neutron component and shield background radioactivity

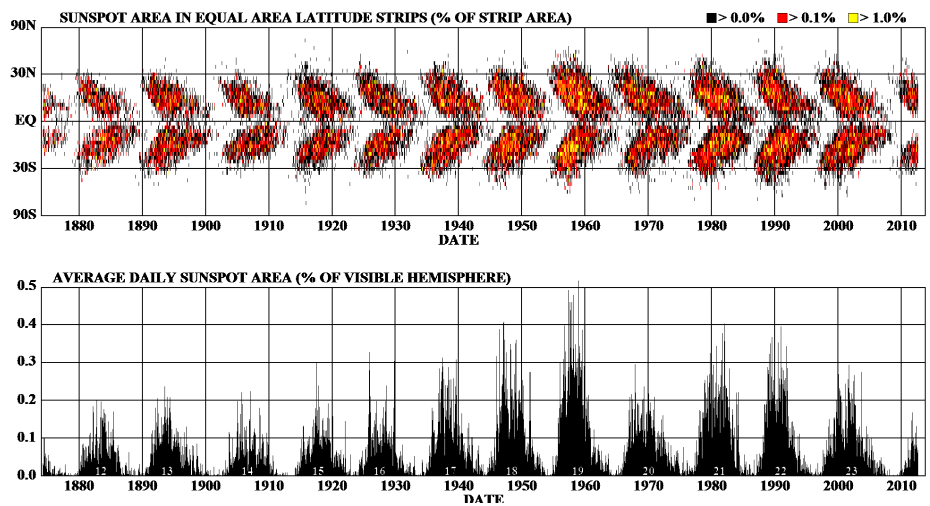




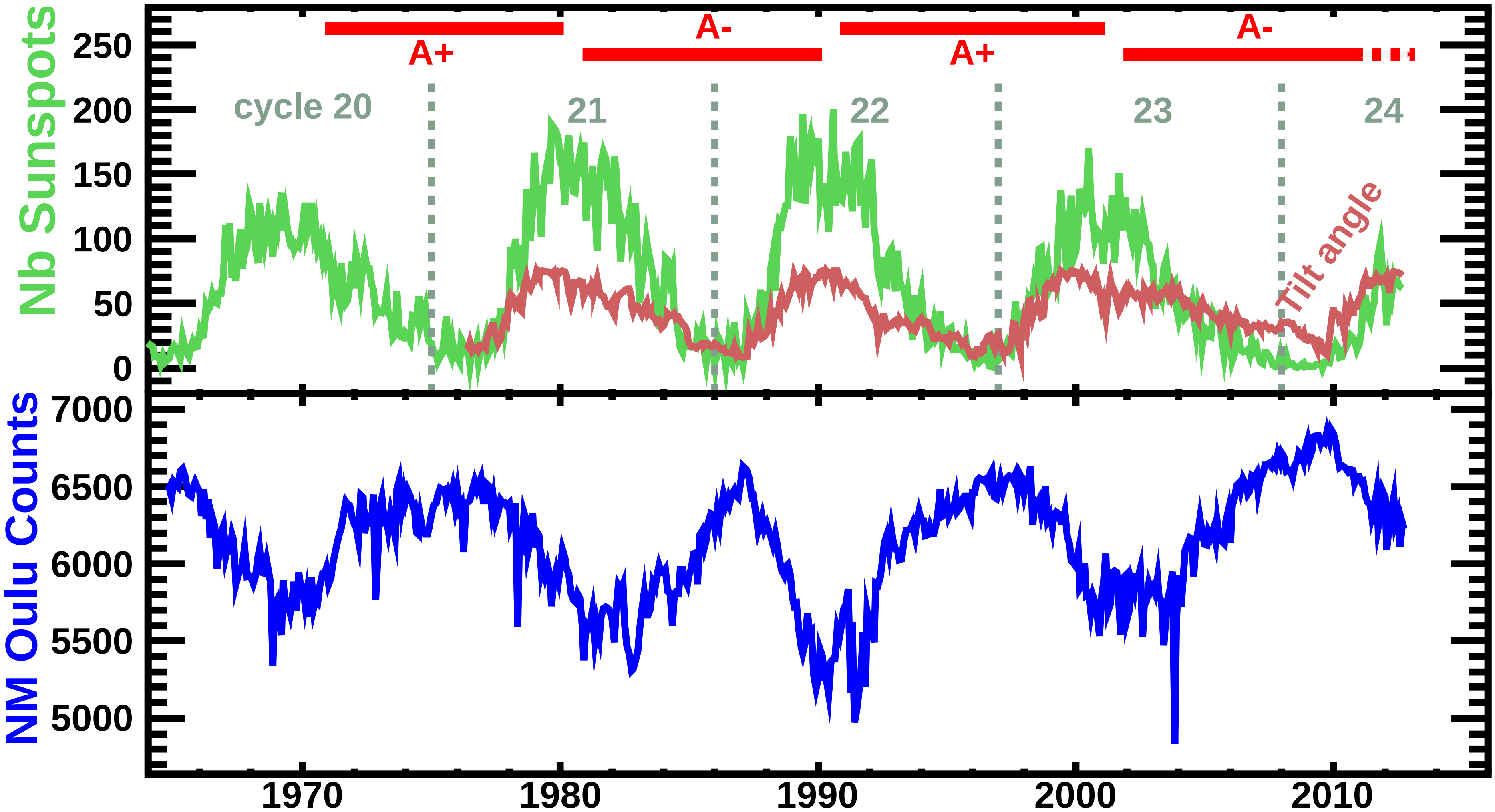
- ✔ measurement of the neutron rate provides information of CR intensity variation

Sunspots

- ✔ the number of sun dark spots (cooler than surrounding photosphere) monitors the Sun activity
  can be as large as 10^5 Km
- ✔ 11 year periodicity
- ✔ solar cycle : from a sunspot minimum to the next one (1st solar cycle : 1755-1766)



Solar cycles

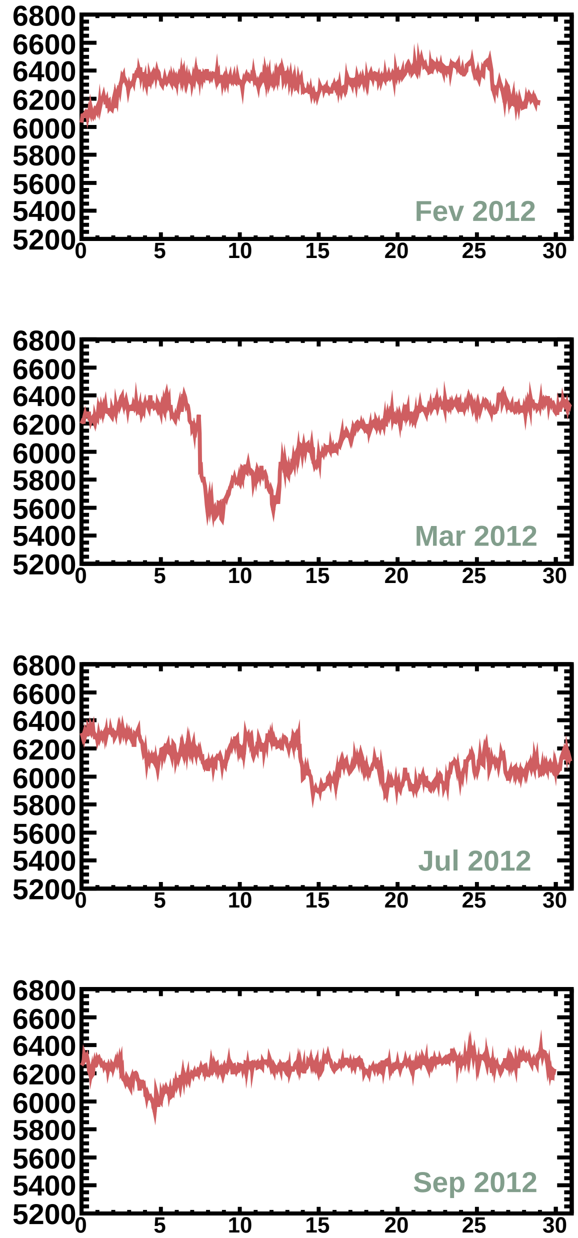


Solar flares

- ✔ A solar flare is a localized explosive release of energy that appears as a sudden, shortlived brightening of an area in the chromosphere
  - ▶ release of electromagnetic radiation and energetic particles
  - ▶ solar brilliance usually measured in optical and X-rays
- ✔ Classified according to the energy released
  X-ray (1-8 Angst) index

E [ergs/$cm^2.s$]		
$C = 10^{-3}$	$M = 10^{-2}$	$X = 10^{-1}$

- ✔ Forbush decrease : cosmic rays flux present a fast decrease (March 2012, NM flux varied of $\sim 10\%$) followed by a recovering periof of ~ 5 days
  - ▶ although more common near solar maximum, occur through all the solar cycle
- ✔ Solar flares visible on 2012 : Jan 27 (X1.7), March 7 (X5.4), July 12 (X1.4),



Cosmic Rays modulation

Parker equation, Force-Field approx

Cosmic Rays modulation

- The flux of travelling galactic cosmic rays experience a **modulation process** when pass in the heliosphere
  - it results from interactions with the solar wind plasma and the embedded solar magnetic field
- *Interaction* processes in heliosphere :
  - **convection** in the solar wind
  - **drift motion** in non-uniform magnetic field
  - **diffusion** in the heliospheric magnetic field inhomogeneities
  - **adiabatic cooling**, i.e. change in the momentum space of particles
- Transport equation results from continuity principle

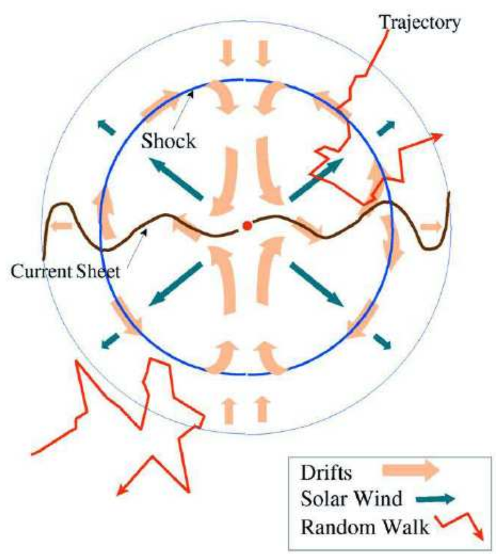
$$\frac{d}{dt} f(\vec{r}, \vec{p}, t) + q = 0$$

f, particle distribution function

q, creation/destruction of particles inside phase-space volume

Transport Parker equation

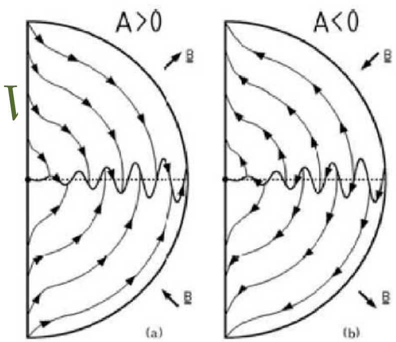
$$
\begin{aligned}
\frac{\partial f}{\partial t} = &- \vec{V}_s \cdot \vec{\nabla} f && \text{Wind plasma convection}\\
&- \vec{V}_D \cdot \vec{\nabla} f && \text{particle drift}\\
&+ \vec{\nabla} \cdot \left(K^S \cdot \vec{\nabla} f \right) && \text{particle diffusion}\\
&+ \frac{1}{3} \left(\vec{\nabla} \cdot \vec{V}_s \right) \frac{\partial f}{\partial \ln P} && \text{Rigidity change}\\
&+ Q && \text{sources/sinks}
\end{aligned}
$$



$f(\vec{r}, p, t)$ distribution function of Galactic CRs (part/$m^3.GV$

$P = \frac{pc}{Ze}$ rigidity (GV)

$\vec{r}$ position vector wrt to the Sun



Drift velocity depend on particle charge (Z) and solar magnetic field polarity (A)

From dist func (f) to differential intensity (J)

$J_P = vP^2 f(\vec{r}, p, t)$ (part/$m^2.sr.s.GV$)

$J_{Tn} = \frac{A}{Z} P^2 f(\vec{r}, p, t)$ (part/$m^2.sr.s.GeV/n$)

Force field solution

- ✔ quasi-stationary state ($\frac{\partial f}{\partial t} = 0$)
- ✔ no sources ($Q = 0$)
- ✔ radial solar wind ($\vec{V}_s = V_s \vec{e}_r$)
- ✔ isotropic diffusion coefficient
- ✔ density distrib function spherically symmetric, $f(r)$
- ✔ no particle drift

$$\boxed{\frac{\partial f}{\partial r} + \frac{V_s}{3}\frac{P}{K}\frac{\partial f}{\partial P} = 0}$$

$\left[\frac{V_s}{3}\frac{P}{K}\right] = GV/m$ (E field)

$K = \beta K_1(r) K_2(P)$

$V_s \sim 400$ Km/s

$K \sim \lambda v \sim (1AU)3\,10^5\ Km/s \sim 10^5\ (Km/s)AU$

$\phi \sim \frac{400}{10^5}(10^2 AU) \sim 0.4GV$

$$\frac{dP}{dr} = \frac{V_s}{3}\frac{P}{K} \rightarrow \int_P^{P_H} \frac{\beta(P')K_2(P')}{P'} dP' = \underbrace{\int_r^{r_H} \frac{1}{3}\frac{V_s(r')}{K_1(r')} dr'}_{\phi(r),\text{force-field param}}$$

Assuming $K_2 \propto P$ and $\beta \sim 1$

$\Rightarrow \boxed{P_H - P = \phi} \Rightarrow \boxed{p_H - p = Ze\phi \equiv \Phi}$

solutions : $f(r, P) = C$ along contours of the charact. eq. (dP/dr)

$$f(r_{1AU}, \underbrace{p_H - \Phi}_{p}) = f(r_H, p_H)$$

$$\Rightarrow \boxed{\frac{J_{1AU}(p)}{J_{LIS}(p_H)} = \left(\frac{p}{p_H}\right)^2 = \frac{E^2 - M^2}{E_H^2 - M^2}}$$

Force field solution

- ✔ quasi-stationary state ($\frac{\partial f}{\partial t} = 0$)
- ✔ no sources ($Q = 0$)
- ✔ radial solar wind ($\vec{V}_s = V_s \vec{e}_r$)
- ✔ isotropic diffusion coefficient
- ✔ density distrib function spherically symmetric, $f(r)$
- ✔ no particle drift

$$\boxed{\frac{\partial f}{\partial r} + \frac{V_s}{3}\frac{P}{K}\frac{\partial f}{\partial P} = 0}$$

$\left[\frac{V_s}{3}\frac{P}{K}\right] = GV/m$ (E field)

$K = \beta K_1(r) K_2(P)$

$$\frac{dP}{dr} = \frac{V_s}{3}\frac{P}{K} \rightarrow \int_P^{P_H} \frac{\beta(P')K_2(P')}{P'} dP' = \underbrace{\int_r^{r_H} \frac{1}{3}\frac{V_s(r')}{K_1(r')} dr'}_{\phi(r),\text{force-field param}}$$

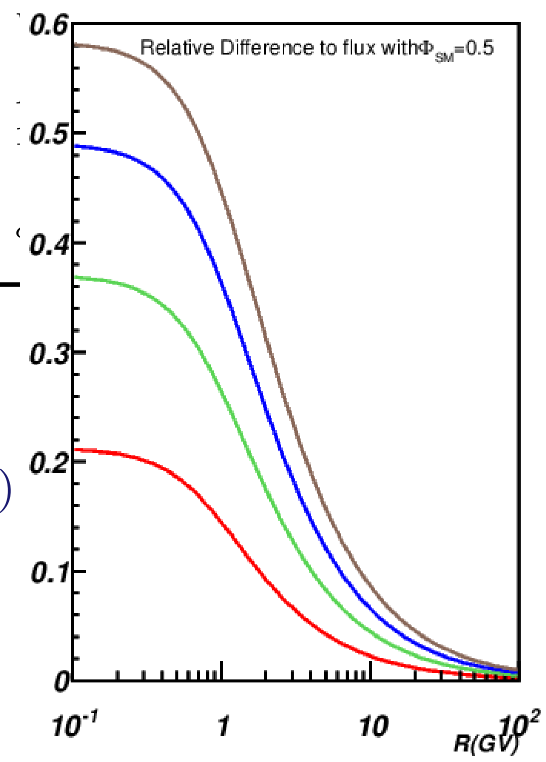
Assuming $K_2 \propto P$ and $\beta \sim 1$

$\Rightarrow \boxed{P_H - P = \phi} \Rightarrow \boxed{p_H - p = Ze\phi \equiv \Phi}$

solutions : $f(r, P) = C$ along contours of the charact. eq. (dP/dr)

$$f(r_{1AU}, \underbrace{p_H - \Phi}_{p}) = f(r_H, p_H)$$

$$\Rightarrow \boxed{\frac{J_{1AU}(p)}{J_{LIS}(p_H)} = \left(\frac{p}{p_H}\right)^2 = \frac{E^2 - M^2}{E_H^2 - M^2}}$$

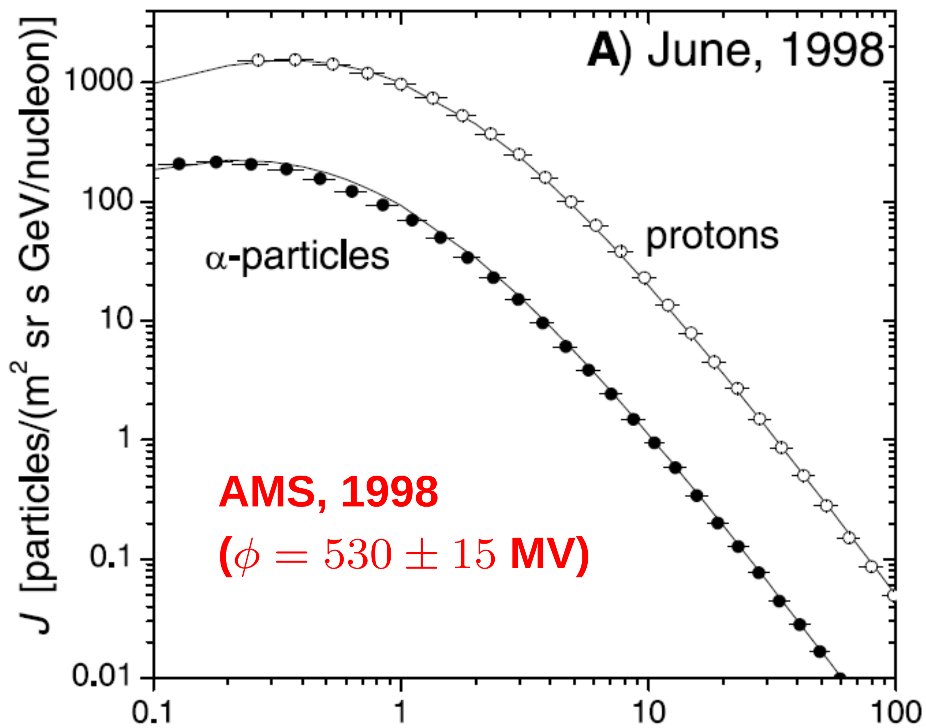


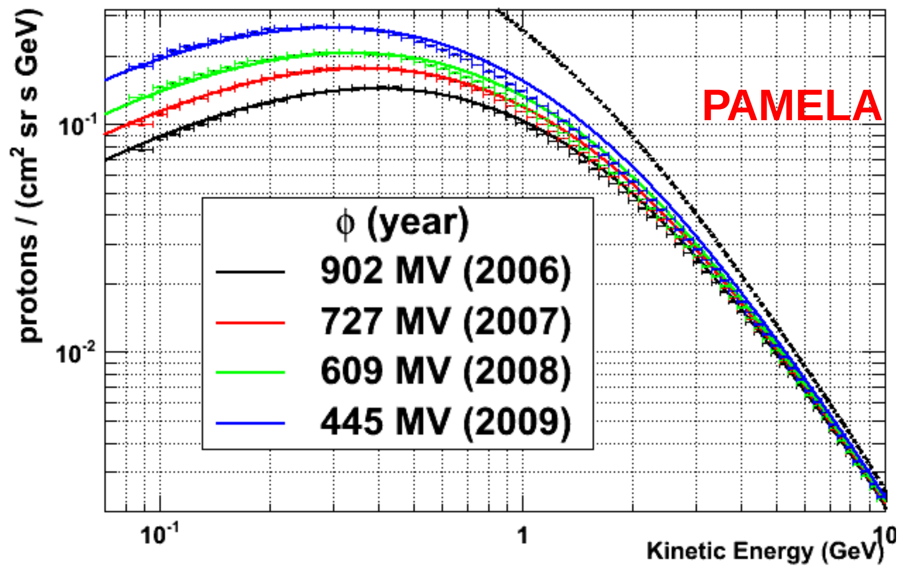
GCRs Force Field modulation

$$J(r,E) = J_{LIS}(E+\Phi)\ \frac{E^2 - M^2}{(E+\Phi)^2 - M^2}$$

$$J(r,T) = J_{LIS}(T+\Phi)\ \frac{T(T+2M)}{(T+\Phi)(T+\Phi+2M)}$$

E, detected energy near Earth $\Phi = Ze\phi$, energy lost by particle in heliosphere





LIS Galprop (PAMELA)

LIS Burger,2000 (AMS)

$J_T = \frac{aP(T)^{-2.78}}{1+bP(T)^{-2.51}}$

$a = 19\ 10^3/m^2.s.sr.GeV/n$

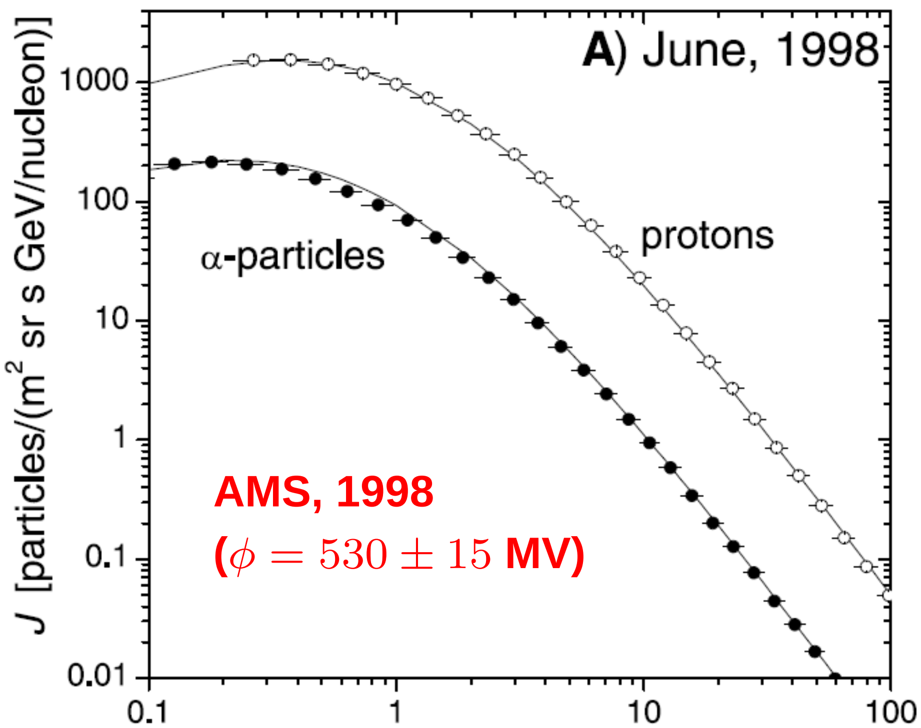
$b = 0.48$

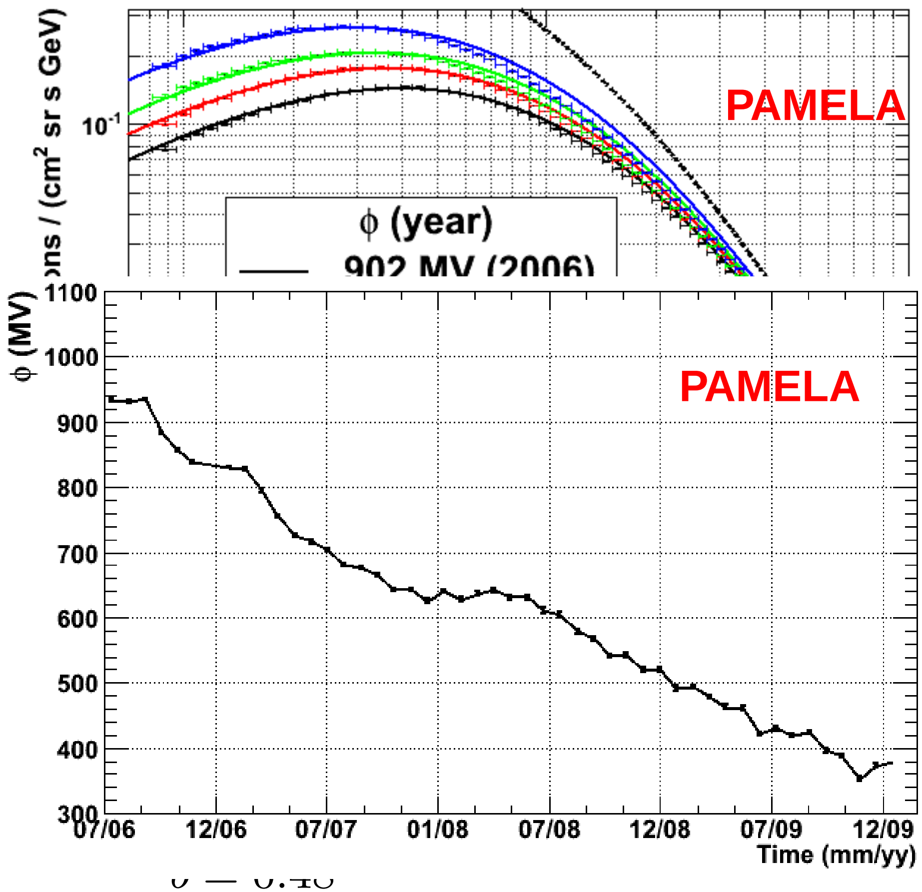
GCRs Force Field modulation

$$J(r,E) = J_{LIS}(E+\Phi)\ \frac{E^2 - M^2}{(E+\Phi)^2 - M^2}$$

$$J(r,T) = J_{LIS}(T+\Phi)\ \frac{T(T+2M)}{(T+\Phi)(T+\Phi+2M)}$$

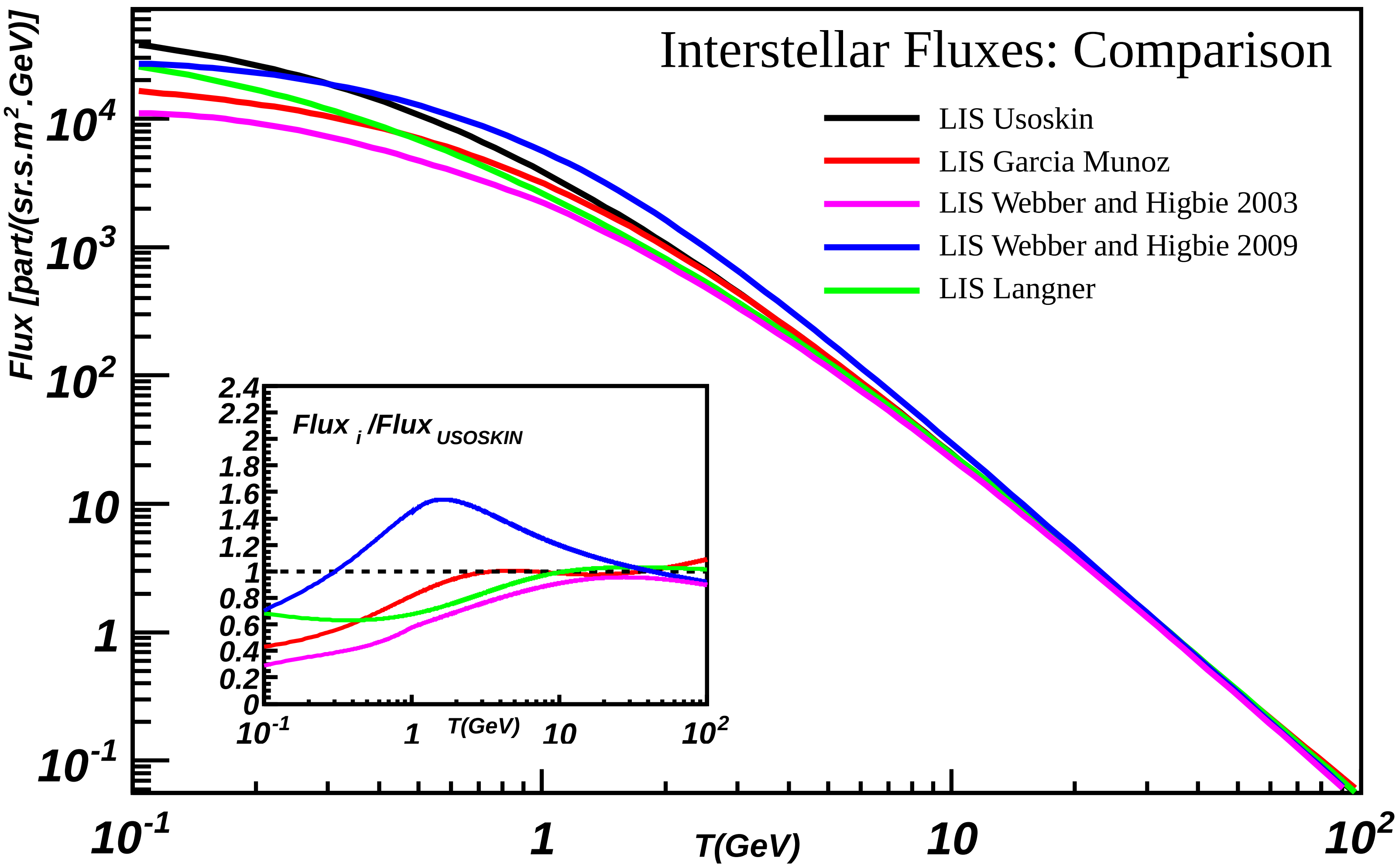
E, detected energy near Earth $\quad \Phi = Ze\phi$, energy lost by particle in heliosphere





LIS fluxes

LIS fluxes are a source of uncertainty...



Solar modulation : 1D solution

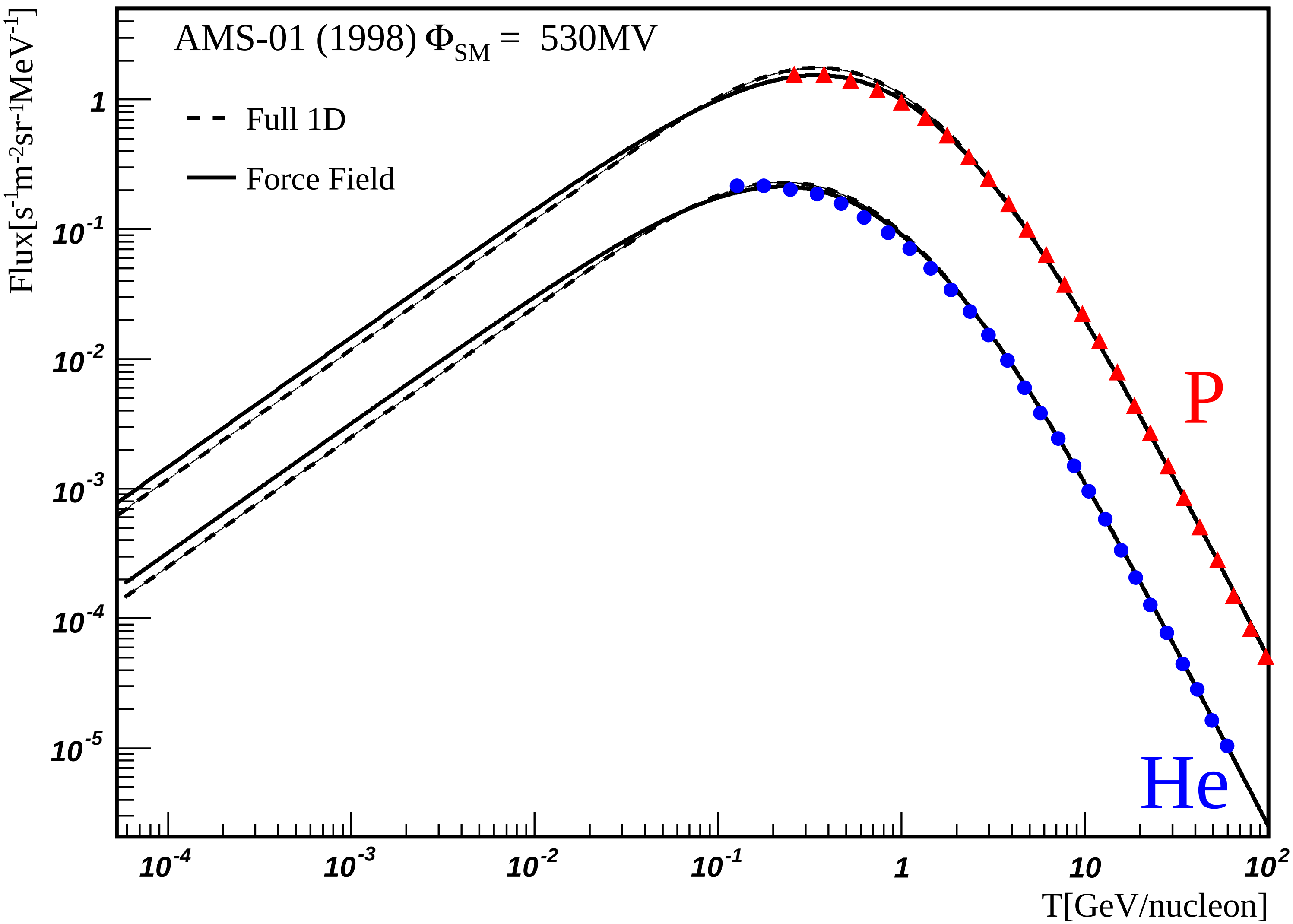
- ✔ quasi-stationary state ($\frac{\partial f}{\partial t} = 0$)
- ✔ no sources ($Q = 0$)
- ✔ radial solar wind ($\vec{V}_s = V_s \vec{e}_r$)
- ✔ isotropic diffusion coefficient : $K = K_0\ K_1(r)\ K_2(P)$
- ✔ density distrib function spherically symmetric, $f(r)$

$$\boxed{V_s \frac{\partial f}{\partial r} - \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 K \frac{\partial f}{\partial r}\right) - \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 V\right)\frac{\partial f}{\partial \ln P} = 0}$$

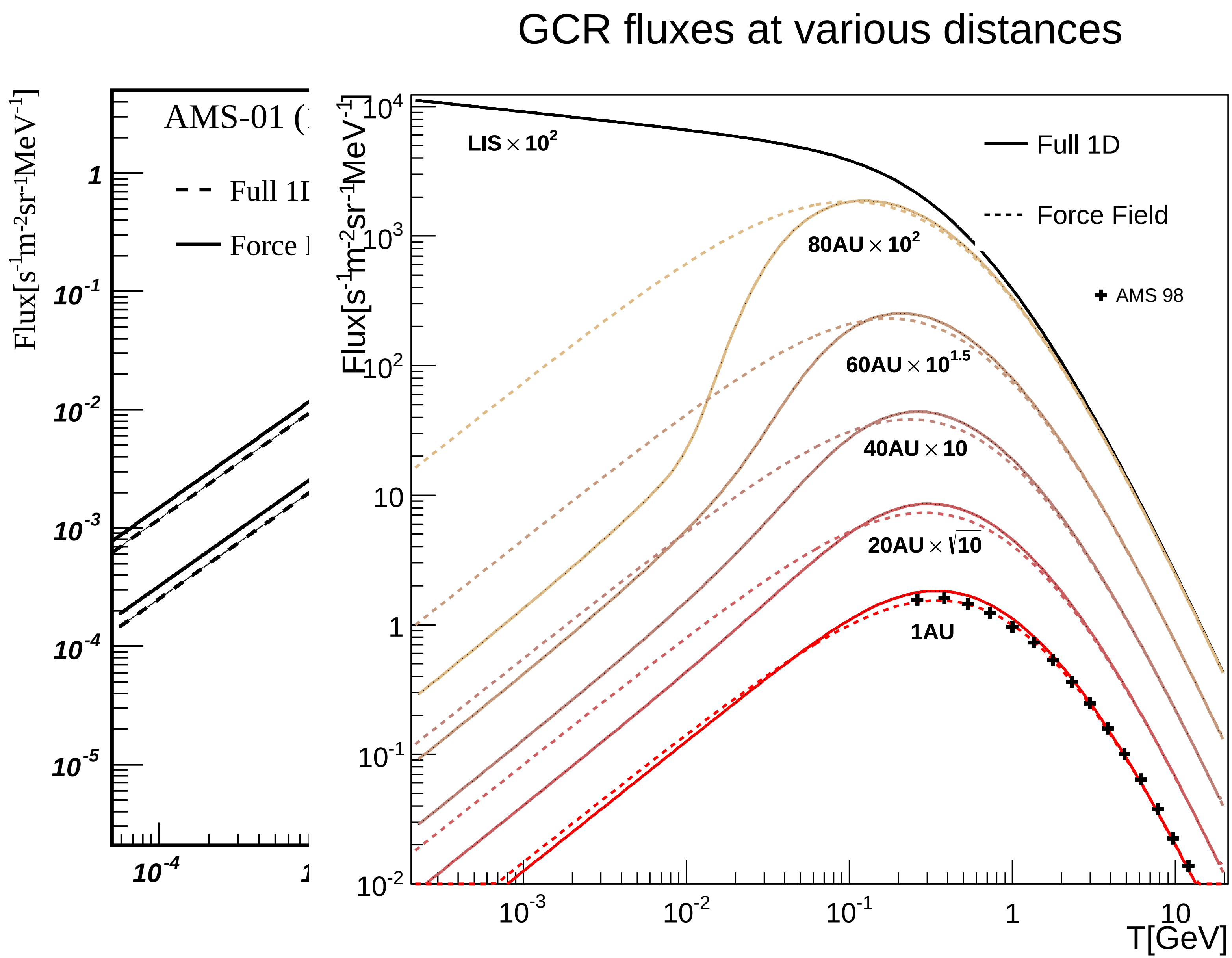
$$\begin{aligned} V_0 &= 400 Km/s \\ V_s &= V_0 \left(1 - e^{-13(r/AU)}\right) \\ K &= 4.38\ 10^{22} \beta\,(P/GV) \quad [cm^2/s] \end{aligned}$$

- ✔ partial differential equation to solve : 2nd order in space, 1st order in energy
- ✔ 2 boundary conditions in space (r_0, r_H) and one initial condition (at high energies $J_T(r,p) = J_{LIS}(p)$)
- ✔ numerical solution stepping in r and $\ln P$

1D solution and AMS01



1D solution and AMS01



CR modulation : higher order solutions

- ✔ The Force-Field analytical and the numerical 1D solutions of the Galactic Cosmic Rays transport equation **do no include** any physics related to the heliosphere magnetic field
- ✔ The lowest-order model that can include the archimedian shaped magnetic field is a 2D (r, θ) solution of the transport equation
  - ► solar rotation effects are averaged

  [R.A. Burger et al., **ApJ674**, 511 (2008)]
- ✔ Stochastic solutions of the multi-dimensional transport equation started to emerge in the last years taking profit from the computing power available in nowadays computers

  [C.Pei et al., **Proc. 31st ICRC**, Paper731 (2009)]

Conclusions and Prospects

- ✔ The 23/24 solar cycle minimum (2008-09) was unusually long
  unprecedented high NM readings were observed together with very high CRs fluxes measured by ACE/CRIS and PAMELA
- ✔ The basic physics processes entering on solar modulation are understood and provide a good description of the CRs modulation (Parker eq)
- ✔ LIS fluxes remain a source of uncertainties for solar modulation models
  Voyagers hopefully will provide direct mesurements of LIS
- ✔ Disentangle the contribution of the different drivers of Solar modulation (tilt angle, diffusion and drift balance, ...) only possible if observations at different times and different places of the heliosphere are available
  current understanding : drift prevails at solar minima and diffusion at maxima
- ✔ The presence in space of two particle identification spectrometers, PAMELA (2006-) and AMS (2011-) allow to measure very precisely CR fluxes
  - ► time monitoring of the charge-sign effects ($e^+/e^-, \bar{p}/p$)
  - ► cross-calibration of neutron monitors and better knowledge of yield functions