Heliospheric modulation of Cosmic rays

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Propagation of Cosmic rays in the Heliosphere

Parker transport equation

Propagation in the heliosphere is described by Parker (1965) equation:

$$\frac{\partial U}{\partial t} = \nabla \cdot (\mathbf{K^S} \cdot \nabla U - \mathbf{V_{sw}} U - \langle \mathbf{v_D} \rangle U) + \frac{1}{3}(\nabla \cdot \mathbf{V_{sw}}) \frac{\partial}{\partial T}(\alpha T U)$$

U is Cosmic Rays number density per unit interval of kinetic energy

Diffusion
Small Scale magnetic Field irregularity

Convection
Solar wind moving out from the Sun

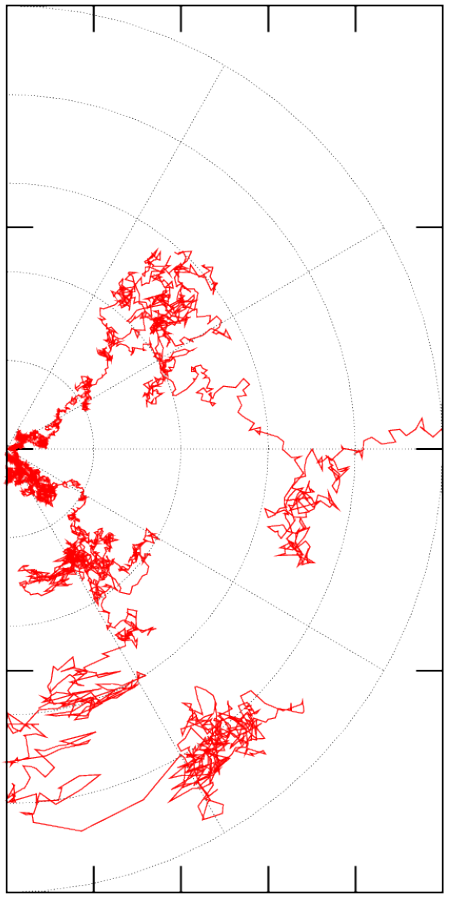
Drift
Large scale magnetic field structure

Energetic Loss
Due to adiabatic expansion of the solar wind

Propagation of CR in the heliosphere is described by Parker (1965) equation:

$$\frac{\partial U}{\partial t} = \nabla\cdot(\mathbf{K^S}\cdot\nabla U - \mathbf{V_{sw}}U - \langle\mathbf{v_D}\rangle U) + \frac{1}{3}(\nabla\cdot\mathbf{V_{sw}})\frac{\partial}{\partial T}(\alpha T U)$$

A Monte Carlo Approach - *Ito's lemma, see e.g. Gardiner, 1985*
The 2D **Hel**iosphere **Mod**ulation Monte Carlo Code: **HelMod**



Stochastic Differential Equations (SDE)

$$dr = \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 K_{rr})dt - \frac{\partial}{\partial \mu}\left(\frac{K_{r\mu}\sqrt{1-\mu^2}}{r}\right)dt + (V_{sw} + v_{d_r})dt + (2K_{rr})^{1/2}R_r\sqrt{dt}$$

$$d\mu = -\frac{1}{r^2}\frac{\partial}{\partial r}\left(rK_{\mu r}\sqrt{1-\mu^2}\right)dt + \frac{\partial}{\partial \mu}\left(K_{\mu\mu}\frac{1-\mu^2}{r^2}\right)dt - \frac{1}{r}v_{d_\mu}\sqrt{1-\mu^2}dt$$
$$+ \frac{-2K_{r\mu}}{r}\left(\frac{1-\mu^2}{2K_{rr}}\right)^{1/2}R_r\sqrt{dt} + \frac{1}{r}\left((1-\mu^2)\frac{K_{\mu\mu}K_{rr} - K_{r\mu}^2}{0.5K_{rr}}\right)^{1/2}R_\mu\sqrt{dt}$$

$$dT = -\frac{\alpha_{rel}T}{3r^2}\frac{\partial V_{sw}r^2}{\partial r}dt$$

2-Dimensional set of SDEs

Details of HelMod modulation code, and how to compute the SDE, could be found in [Bobik et al. Ap.J. 2012, 745:132]

The interplanetary magnetic field

The Sun's magnetic field is transported with the Solar wind into space, forming the so-called Heliospheric Magnetic Field (HMF)

Parker Field

+

Jokipii & Kota, 1989
Langner, 2004

$$\mathbf{B} = \begin{cases} \frac{A}{r^2}\left[\mathbf{e}_r + \frac{r}{r_b}\delta(\theta)\mathbf{e}_\theta - \Gamma\mathbf{e}_\phi\right]\left[1 - 2H\left(\theta - \theta'\right)\right] & \text{Polar regions} \\ \frac{A}{r^2}\left[\mathbf{e}_r - \Gamma\mathbf{e}_\phi\right]\left[1 - 2H\left(\theta - \theta'\right)\right] & \text{elsewhere} \end{cases}$$

$$\delta(\theta) = \frac{\delta_m}{\left[1 - 2H\left(\theta - \theta'\right)\right]\sin\theta}$$

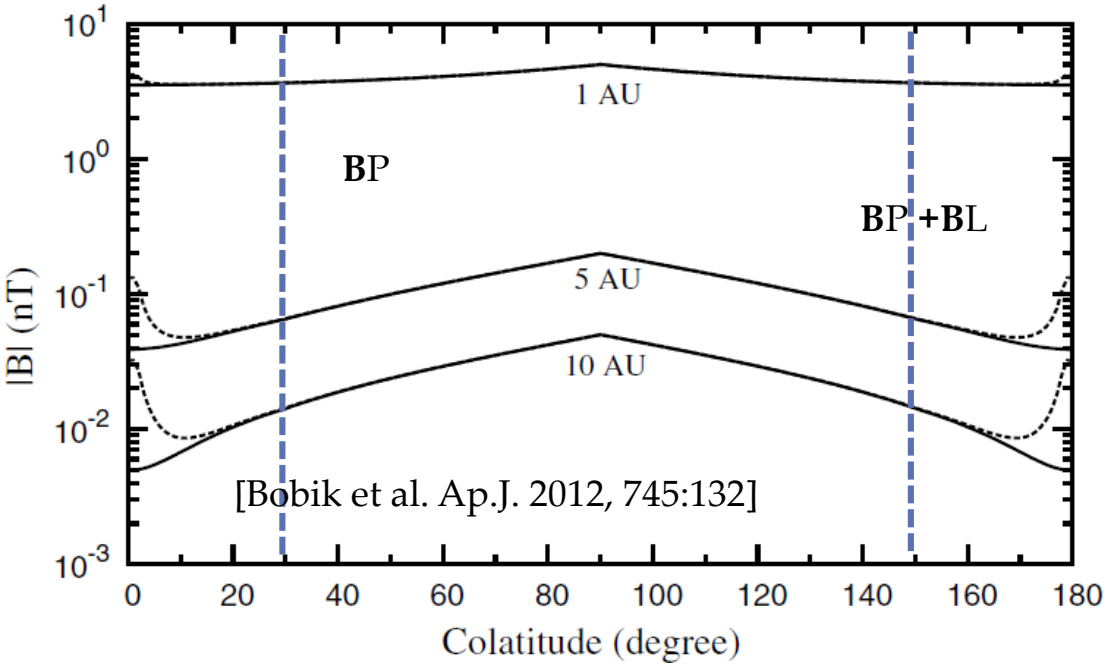
$$\mathbf{B}_P = \frac{A}{r^2}\left[\mathbf{e}_r - \left(\frac{(r - r_0)\omega\,\sin\theta}{V_{sw}}\right)\mathbf{e}_\phi\right]\left[1 - 2H(\theta - \theta')\right]$$

$$\mathbf{B}_L = + \frac{A\delta_m}{r_0 r\,\sin\theta}\mathbf{e}_\theta$$

The Polar Correction **B**L is evaluated only

For $\theta < 30°$ and $\theta > 150°$

of solar colatitude



Diffusion

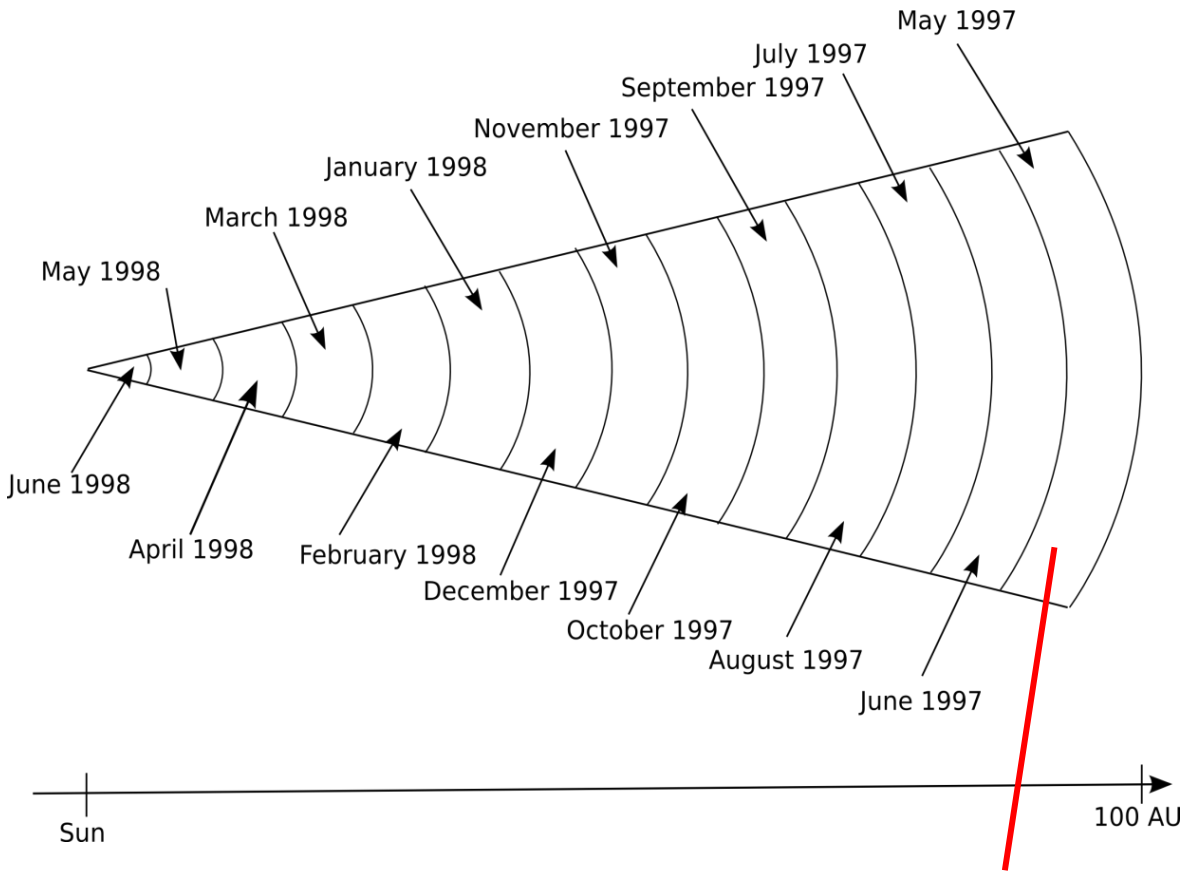
In the *magnetic field line reference* the diffusion tensor is

$$K_{ik} = \begin{vmatrix} K_{\perp r} & -K_A & 0 \\ K_A & K_{\perp\theta} & 0 \\ 0 & 0 & K_{||} \end{vmatrix} \Longleftrightarrow \begin{aligned} K_{||} &= \frac{\beta}{3} K_0 \frac{P}{1\mathrm{GV}} \left(1 + \frac{r}{1\ \mathrm{AU}}\right) \\ K_{\perp\theta} &= K_{\perp r} = \rho_k K_{||}, \end{aligned}$$

[Strauss et al, 2011]

$K_0(t)$ is the modulation parameter obtained using **cosmic ray** measured with neutron monitor at different latitudes

- $K_0(t)$ takes into account the rough **integrated effects** on GCR modulation as seen at the Earth position
- We apply modulation inside an effective spherical volume of 100 AU
- Changing Heliosphere dimensions (**80 – 120 AU**) modulated spectra do not differ significantly, for **rigidity > 1 GV** (> **400 MeV**)



We divide the Heliosphere in 15 regions.
each one equivalent to the average of solar activity in periods before the experiment

Parameters in each region are

Diffusion parameter

Tilt angle of the Neutral Sheet

Magnetic Field Magnitude at Earth

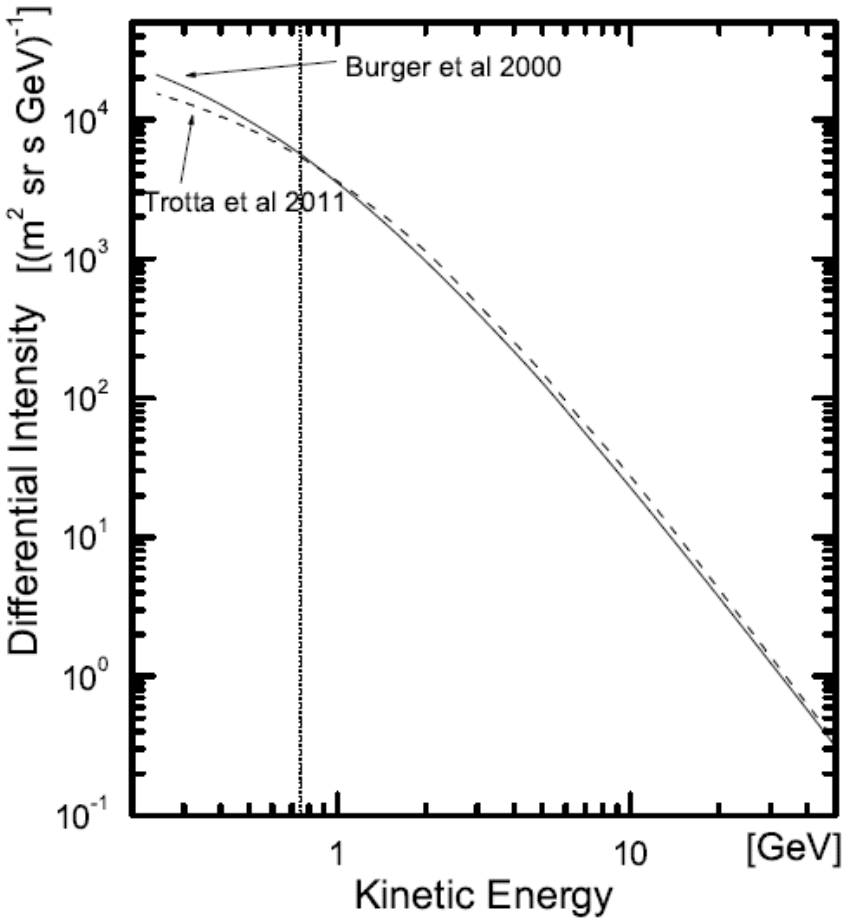
Solar Wind Speed

Protons LIS

1. Model(s) independent from the LIS

2. Transmission function approach

3. Possibility use/test different LIS



Comparison between the Proton LIS from GALPROP (dash line, Trotta et al., 2011) and BPH-LIS (Solid line, Burger et al., 2000). The short-dot line correspond to 1 GV.

HelMod – selected results

error-weighted
root mean square of
the relative difference
between experimental data
and those resulting from
simulated differential
intensities

$$\eta_{\mathrm{rms}} = \sqrt{\frac{\sum_i (\eta_i/\sigma_{\eta,i})^2}{\sum_i 1/\sigma_{\eta,i}^2}}$$

$$\eta_i = \frac{f_{\mathrm{sim}}(T_i) - f_{\mathrm{exp}}(T_i)}{f_{\mathrm{exp}}(T_i)}$$

Observations	"L" Model	"R" Model
BESS–1999	8.7	8.0
BESS–2000	16.2	15.8
BESS–2002	12.7	15.0

Observations	"L" Model	"R" Model
BESS–1997	9.2	17.7
AMS–1998	4.6	7.9
BESS–1998	9.1	14.1
PAMELA–2006/08	7.1	13.4

Table 2 and 4

Systematic Investigation of Solar Modulation of Galactic Protons for Solar Cycle 23 using a Monte Carlo Approach with Particle Drift Effects and Latitudinal Dependence

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ABSTRACT

A propagation model of galactic cosmic protons through the Heliosphere was implemented using a 2-D Monte Carlo approach to determine the differential intensities of protons during the solar cycle 23. The model includes the effects due to the variation of solar activity during the propagation of cosmic rays from the boundary of the heliopause down to Earth's position. Drift effects are also accounted for. The simulated spectra were found in agreement with those obtained with experimental observations carried out by BESS, AMS and PAMELA collaborations. In addition, the modulated spectrum determined with the present code for the year 1995 exhibits the latitudinal gradient and equatorial southward offset minimum found by Ulysses fast scan in 1995.

Subject headings: Solar modulation, Interplanetary space, Cosmic rays propagation

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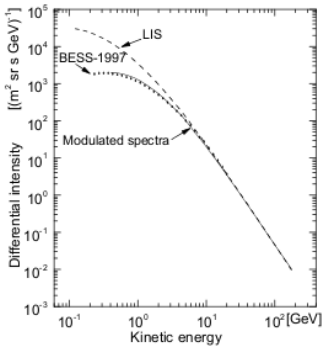
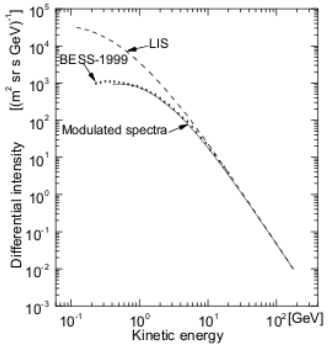
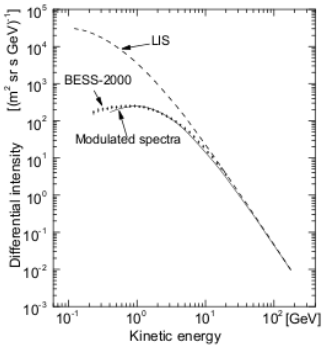
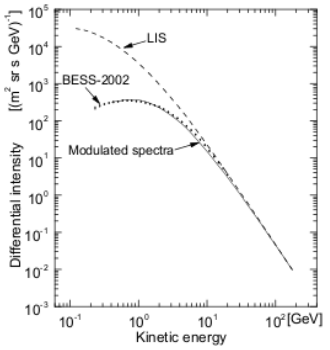
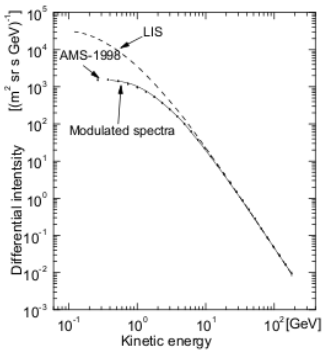
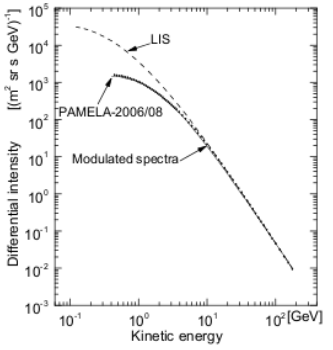












HelMod – selected results

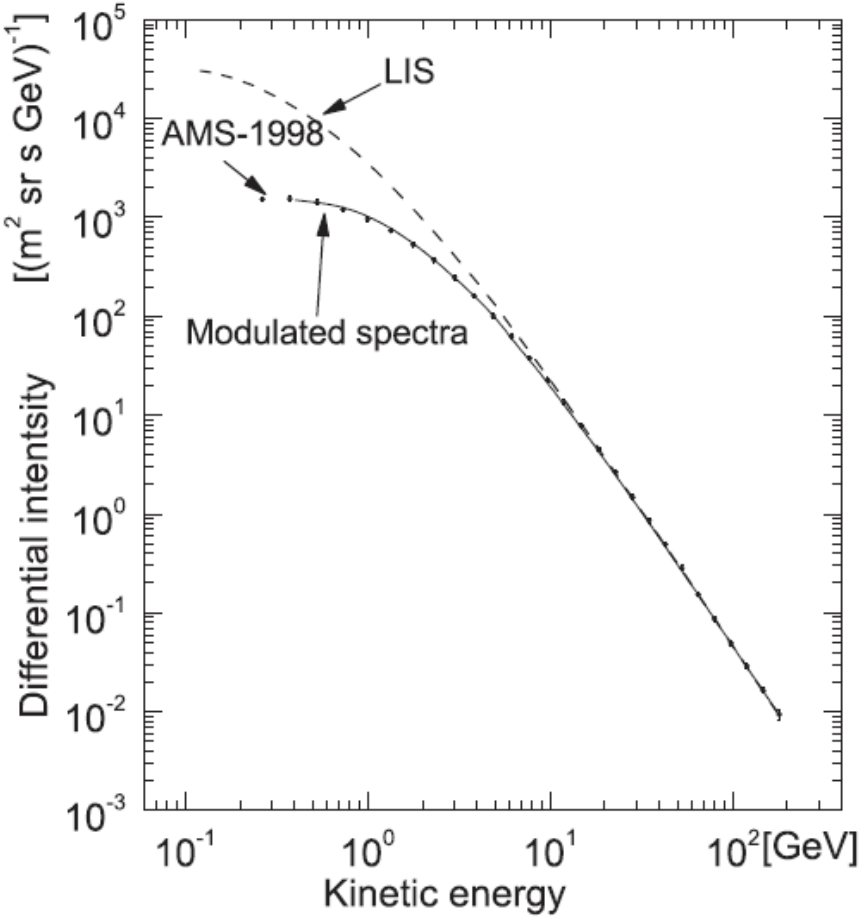


Figure 8. Differential intensity determined with the HelMod code (continuous line) compared to the experimental data of AMS–1998; the dashed line is the LIS (see the text).

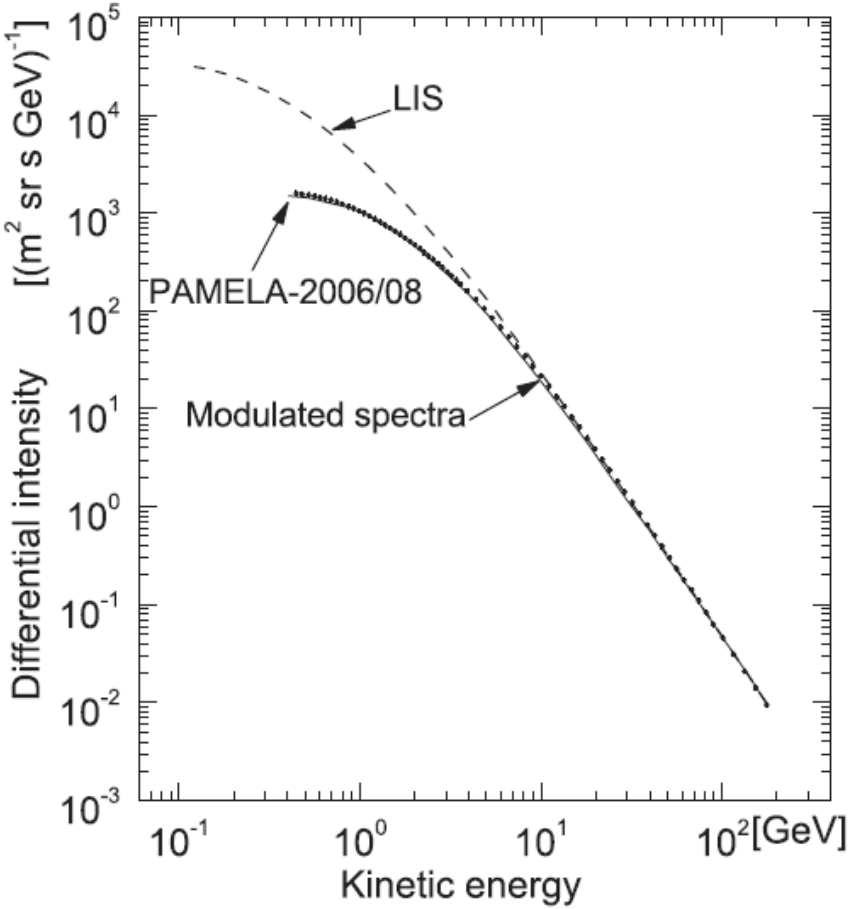


Figure 10. Differential intensity determined with the HelMod code (continuous line) compared to the experimental data of PAMELA–2006/08; the dashed line is the LIS (see the text).

Bobik P. et al., Systematic Investigation of Solar Modulation of Galactic Protons for Solar Cycle 23 Using a Monte Carlo Approach with Particle Drift Effects and Latitudinal Dependence, The Astrophysical Journal, Volume 745, Issue 2, 21 pp. , 2012

HelMod – selected results

antiproton over proton ratio at 1AU

Proton & antiproton LIS from : Casaus, J.: The AMS-02 experiment on the ISS, J. Phys. Conf. Ser., 171, 012045, 2009 obtained from GALPROP

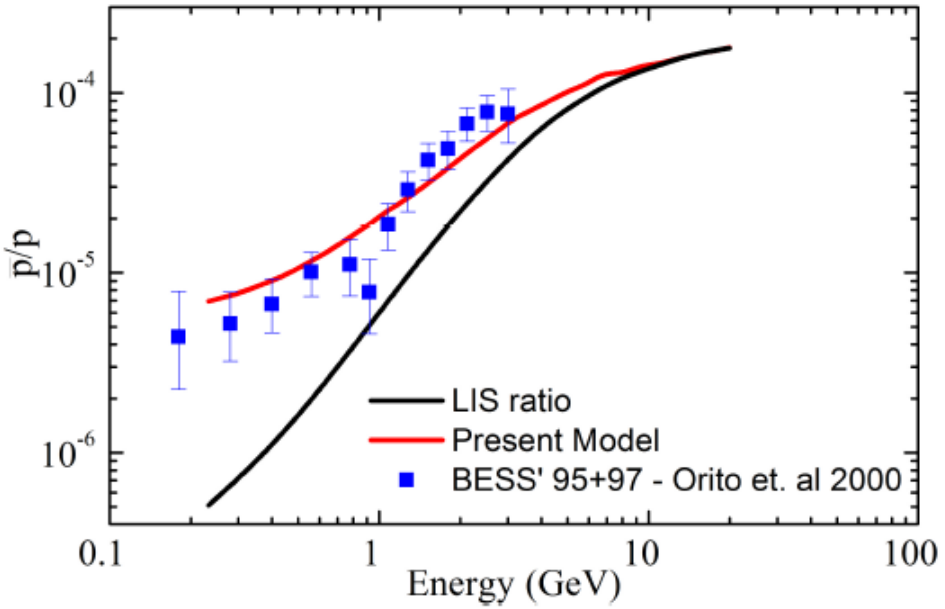


Fig. 2. Comparison of simulated $\bar{p}/p$ ratio at 1 AU and experimental data: BESS (1997).

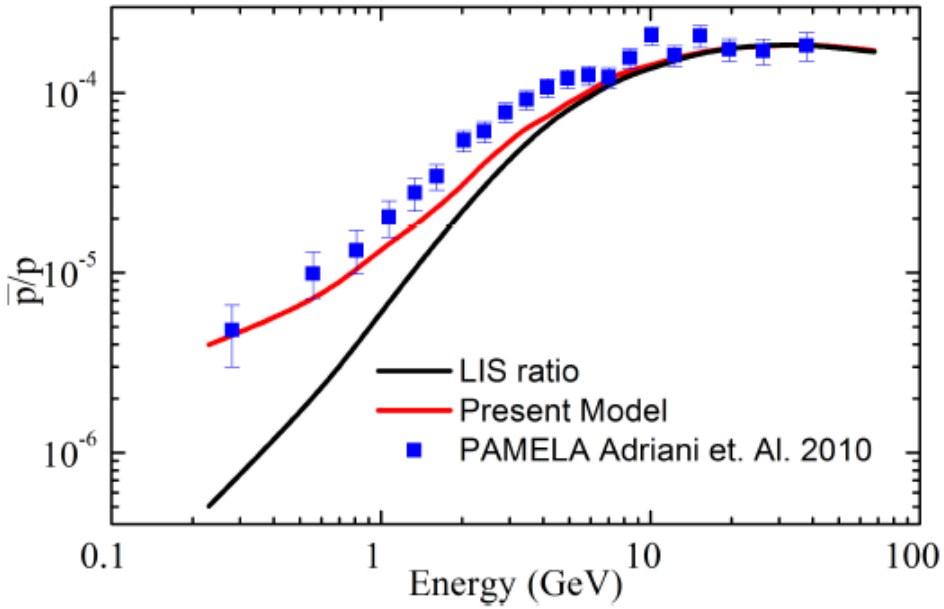
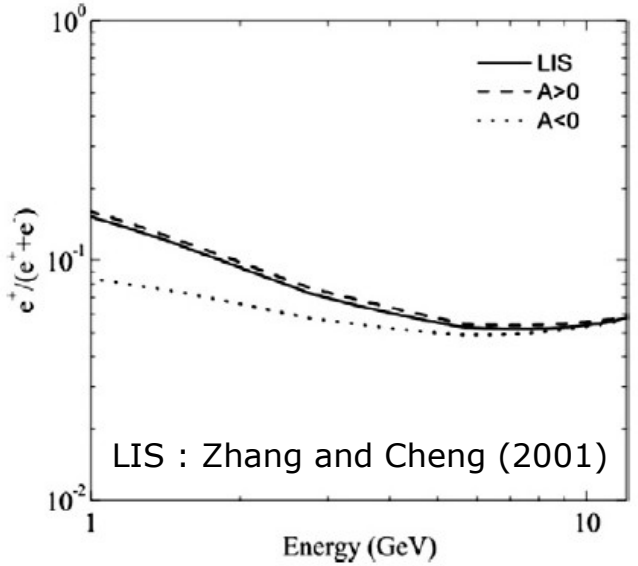


Fig. 3. Comparison of simulated $\bar{p}/p$ ratio at 1 AU and experimental data: PAMELA (2007–2008).

P. Bobik, M. et al., Antiproton modulation in the Heliosphere and AMS-02 antiproton over proton ratio prediction, *Astrophys. Space Sci. Trans.*, 7, 245–249, 2011

HelMod – selected results



$e^+/(e^+ + e^-)$

Fig. 2. The cosmic ray positron fraction evaluated for a period corresponding to a typical solar minimum with both magnetic field polarities.

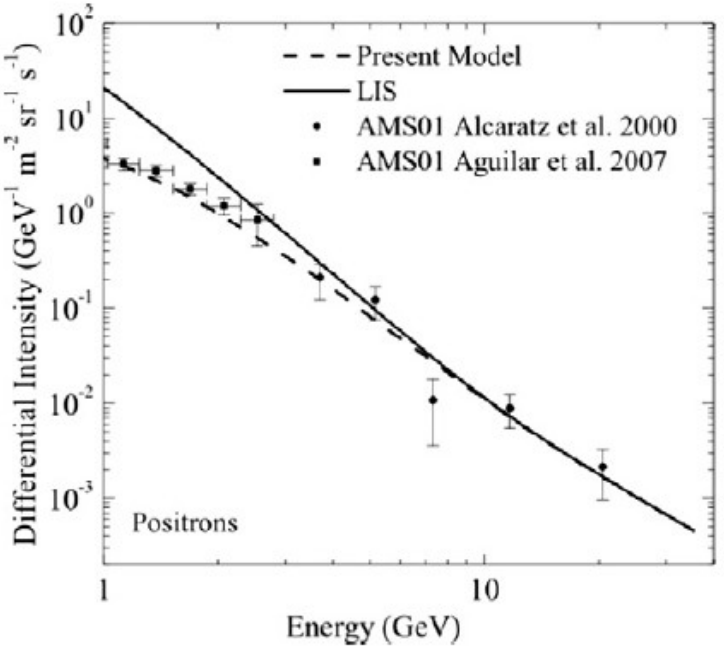


Fig. 4. Simulated positron spectrum for AMS-01 mission (1998).

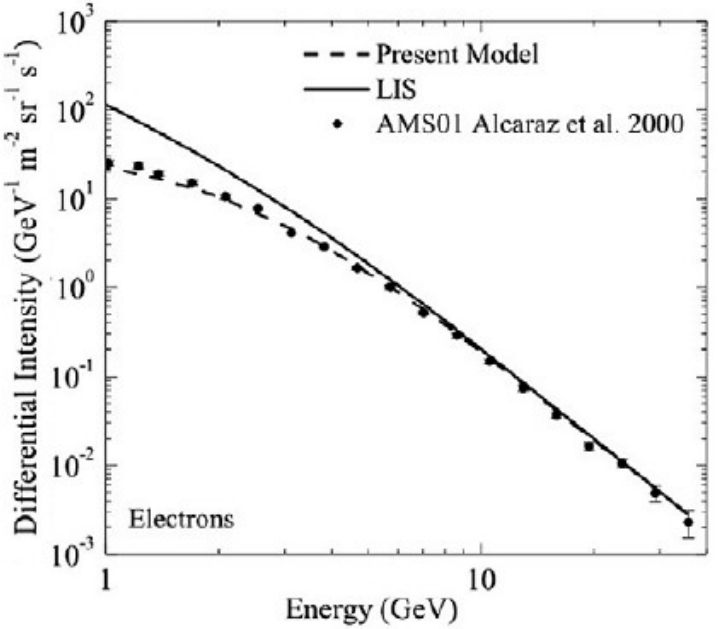


Fig. 3. Simulated electron spectrum for AMS-01 mission (1998).

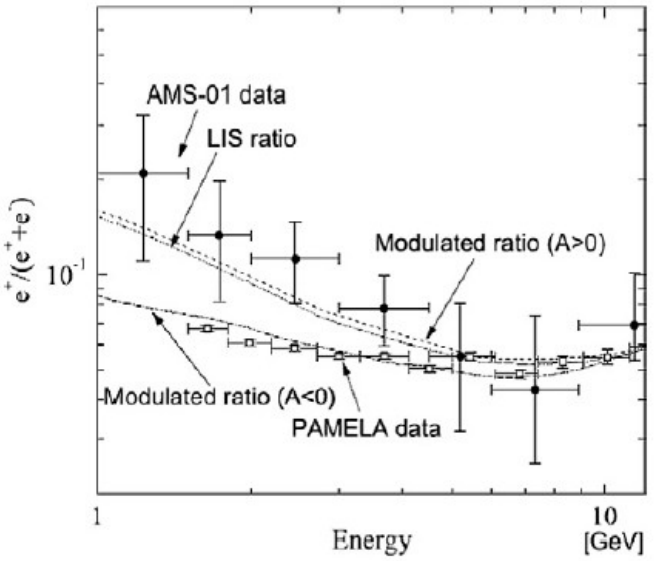
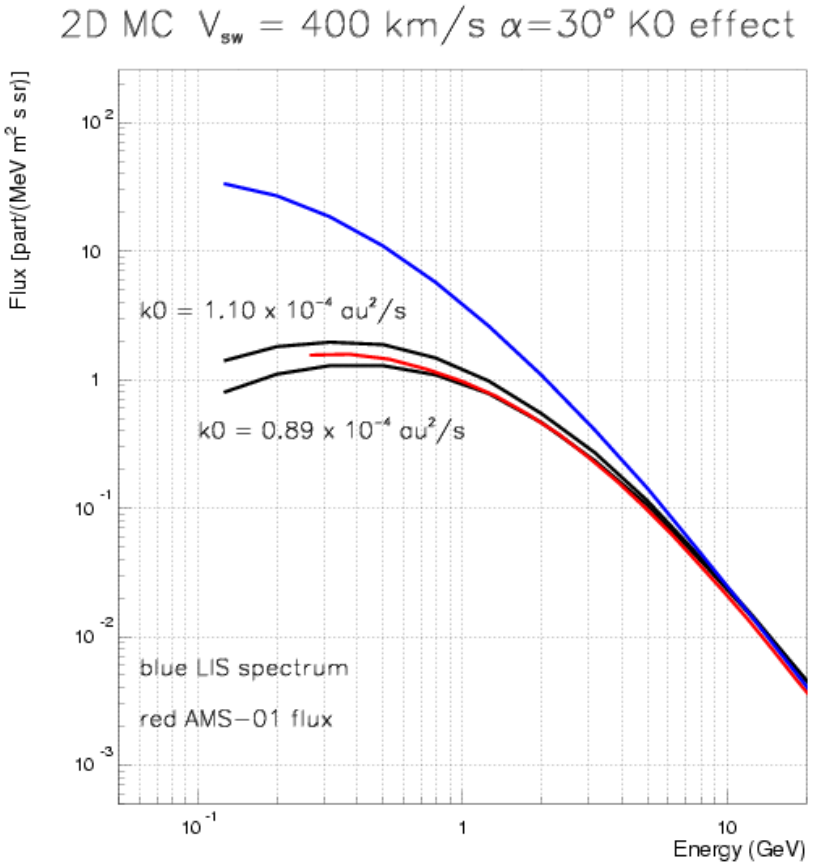


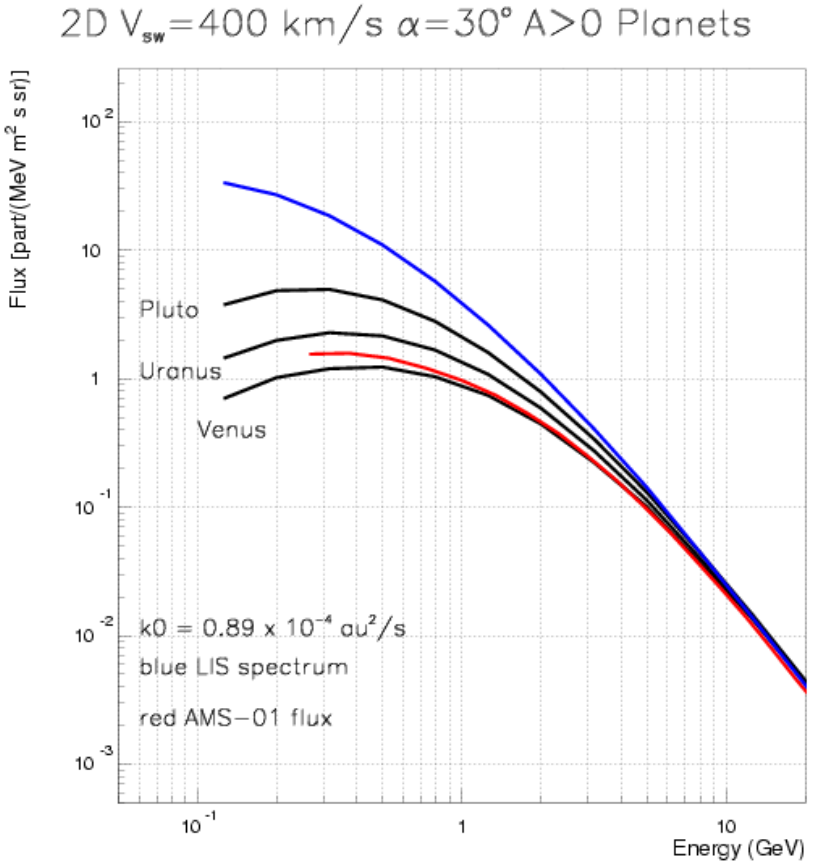
Fig. 5. Simulated cosmic ray positron fraction for AMS-01 (1998) and PAMELA (2006–2008).

S. Della Torre et al., Effects of solar modulation on the cosmic ray positron fraction, Advances in Space Research 49, 1587–1592, 2012

HelMod – selected results spectras at planet orbits



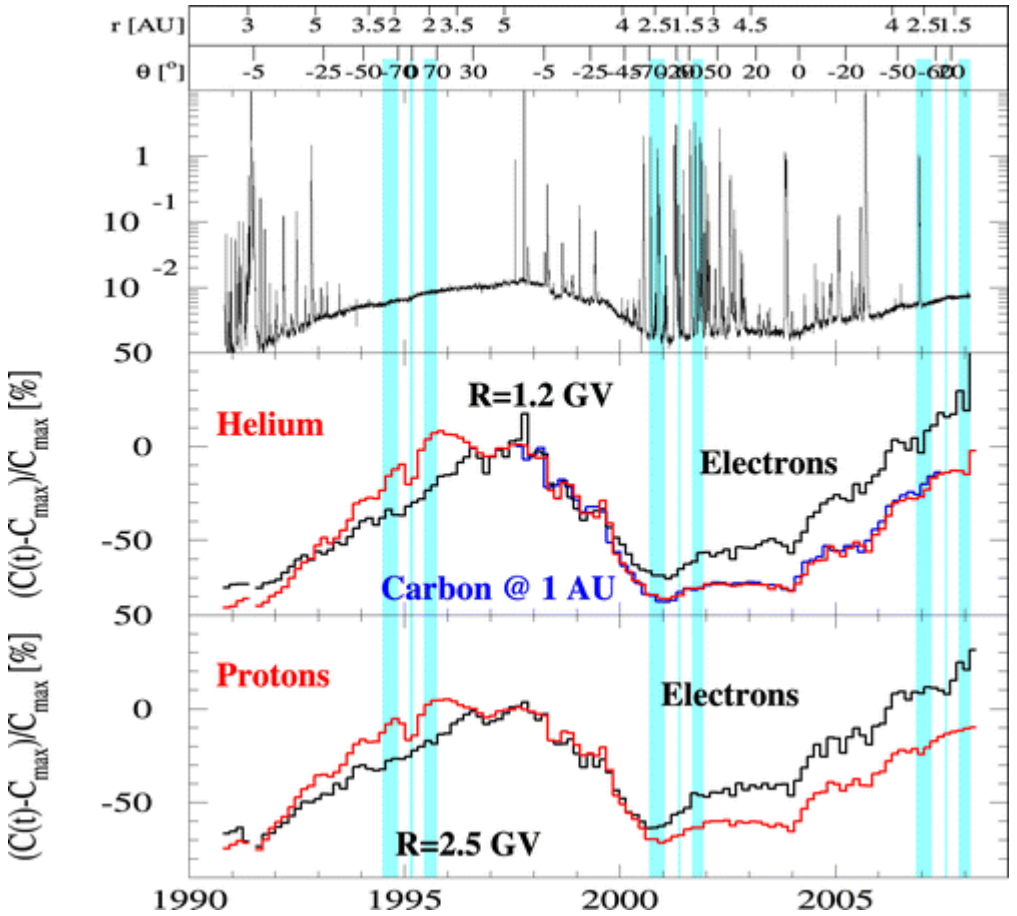
Evaluated primary proton flux at Earth (1AU) for positive solar period.



Proton flux at different distances (planets) in the solar system.

Latitudinal CR intensity dependence

From '90s up to 2010 ESA/NASA Ulysses mission explored the heliosphere outside the ecliptic plane



[Heber et al. Ap.J. 2008, 689:1443]

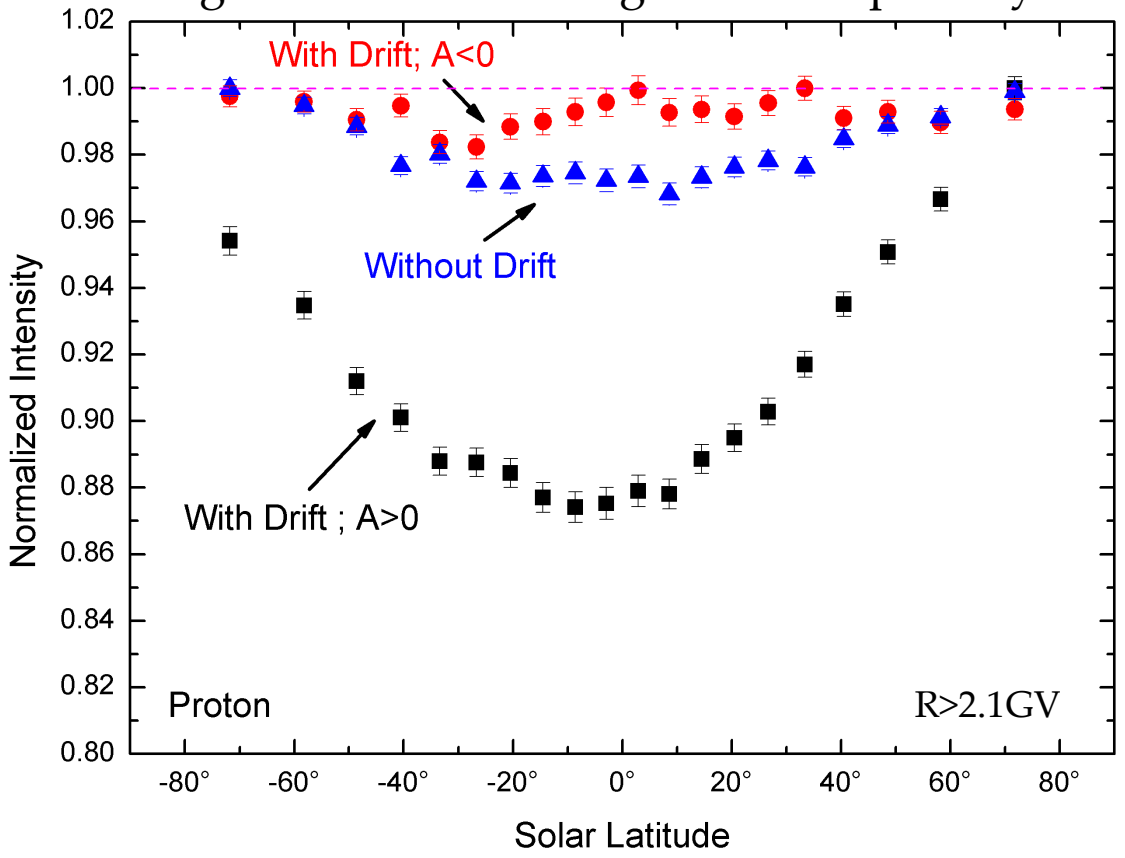
K.E.T. Instruments measured cosmic protons and electrons in energy range greater than 0.2 GeV.

The fast scan in 1995 (A>0) showed the presence of a latitudinal gradient of proton in the inner heliosphere. This gradient vanished during the 2007 (A<0) fast scan.
Electrons show opposite behavior.

[see e.g. Heber et al. Ap.J. 2008, 689:1443 and reference therin]

Drift effect on latitudinal gradient

We use HelMod Code with present model of $K_{||}$ to evaluate the latitudinal gradient in both magnetic field polarity.

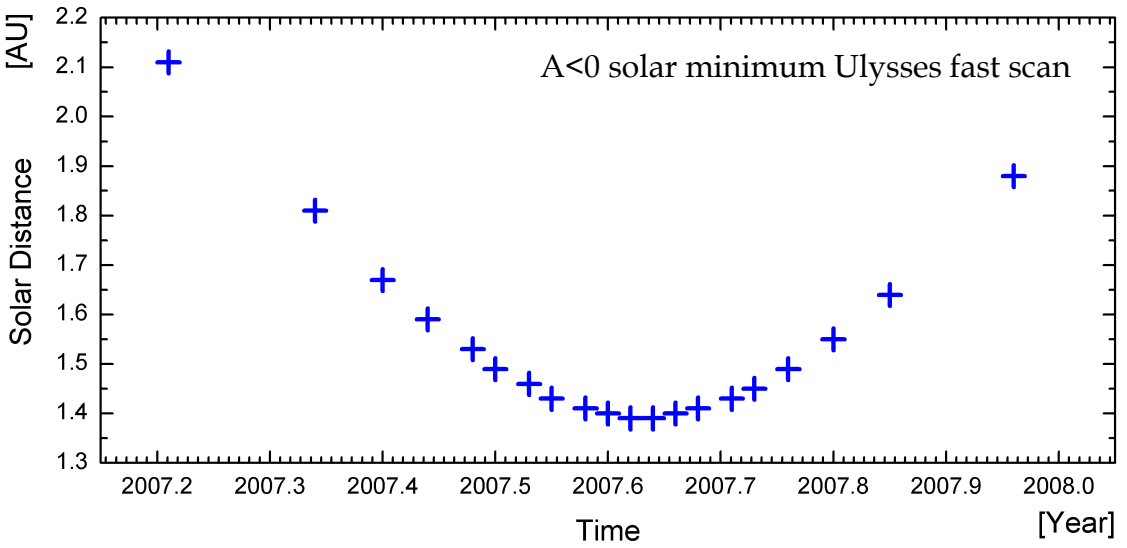


The presence (or not) of a latitudinal gradient is related to Drift mechanism in the heliosphere.

Since drift is related to the product of charge (q) and field Polarity (A), with electron opposite behaviors appears, in qualitatively agreement with Ulysses analysis

Data comparison

To compare our results with Ulysses data we evaluate the Cosmic rays intensity during the both two fast scans at the same distance and latitude of Ulysses Spacecraft (IU)

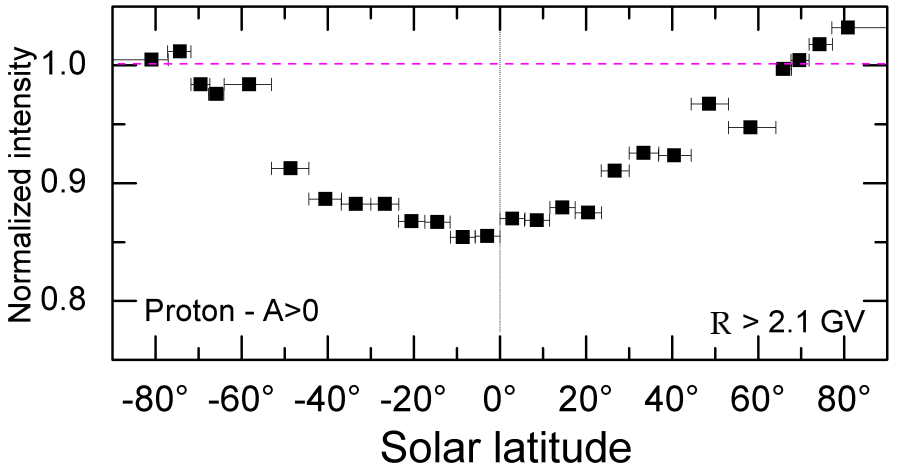


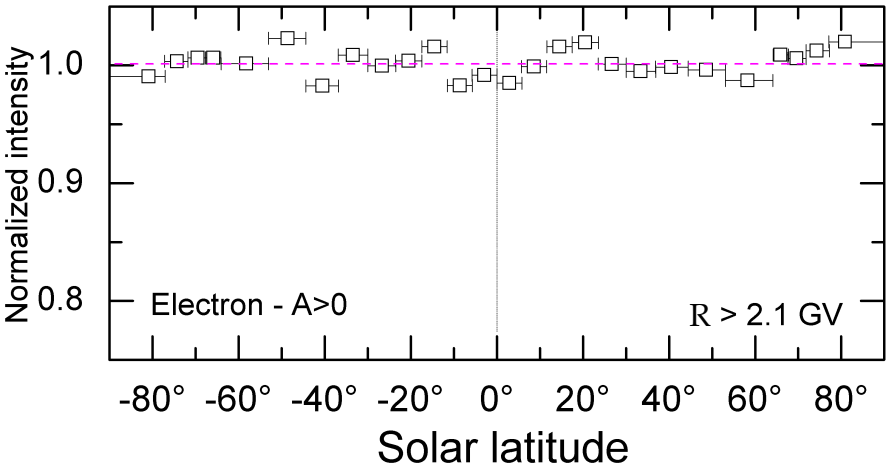
To take in to account the time variation of the Cosmic rays intensity
We evaluate also the intensity at the same time at 1AU on ecliptica (IE) and renormalize the ratio IU/IE in order to have 1 at south pole (-90° ~ -70°)

The same is done both for Proton and Electron

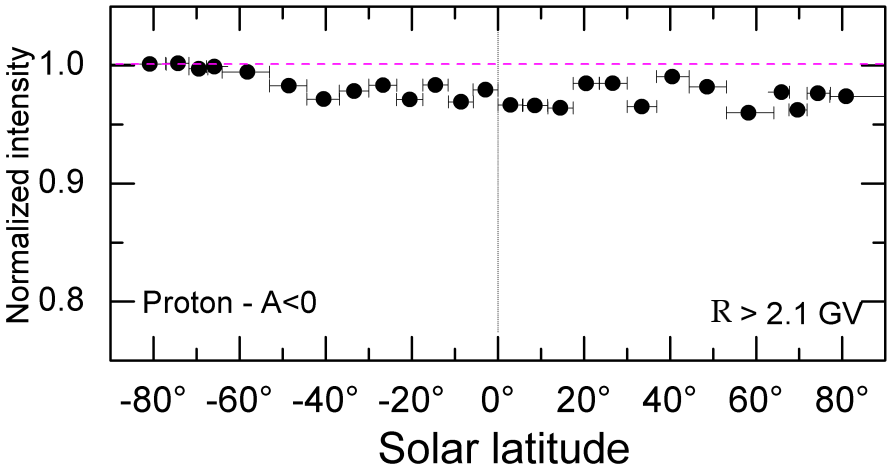
Results

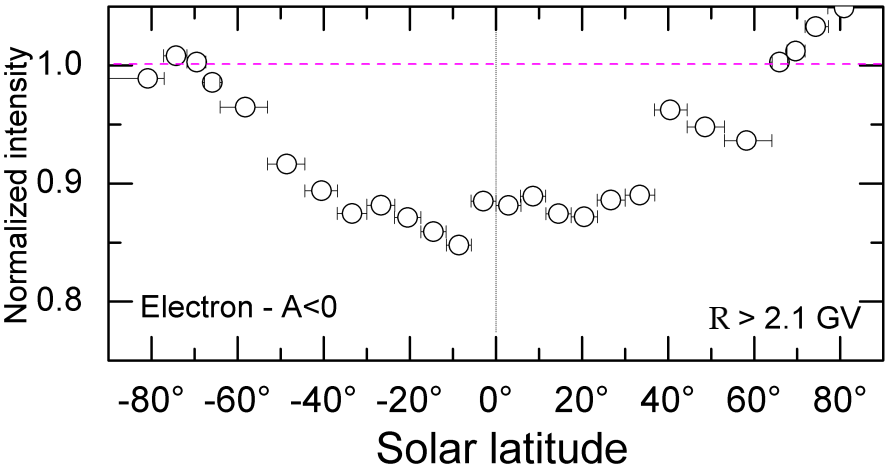
A>0 Ulysses Fast Scan





A<0 Ulysses Fast Scan





S. Della Torre et al., A Monte Carlo study for 2-D Heliospheric modulation effects, ECRS, Moscow, 2012

Results

Cosmic Ray Modulation studied with HelMod Monte Carlo tool and comparison with Ulysses Fast Scan Data during consecutive Solar Minima

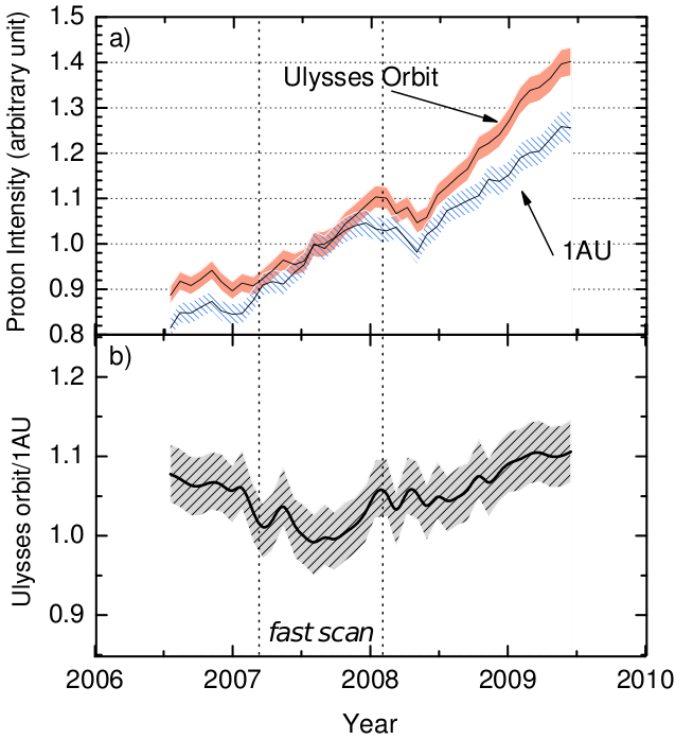


Figure 1: Panel (a): Comparison of HelMod proton intensities at rigidity$\sim$ 1.7GV along Ulysses orbit (red) with that at Earth orbit (blue); the proton intensities are normalized to the value corresponding to the closest approach of Ulysses spacecraft to Earth orbit. Panel (b): Proton intensity along Ulysses orbit divided with those at Earth as computed by HelMod. For both plot the shadow represents the statistical and systematic.

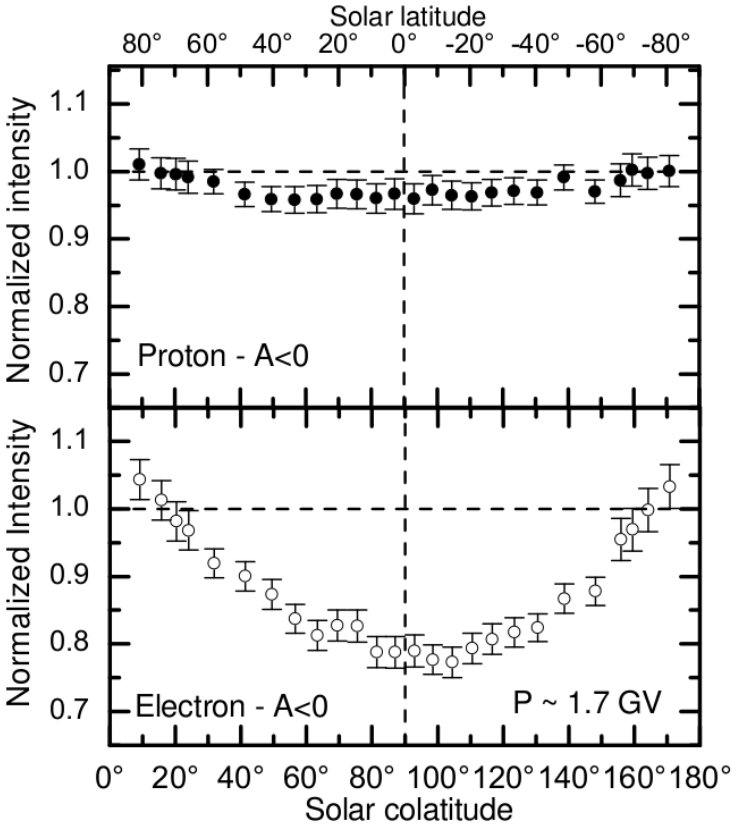
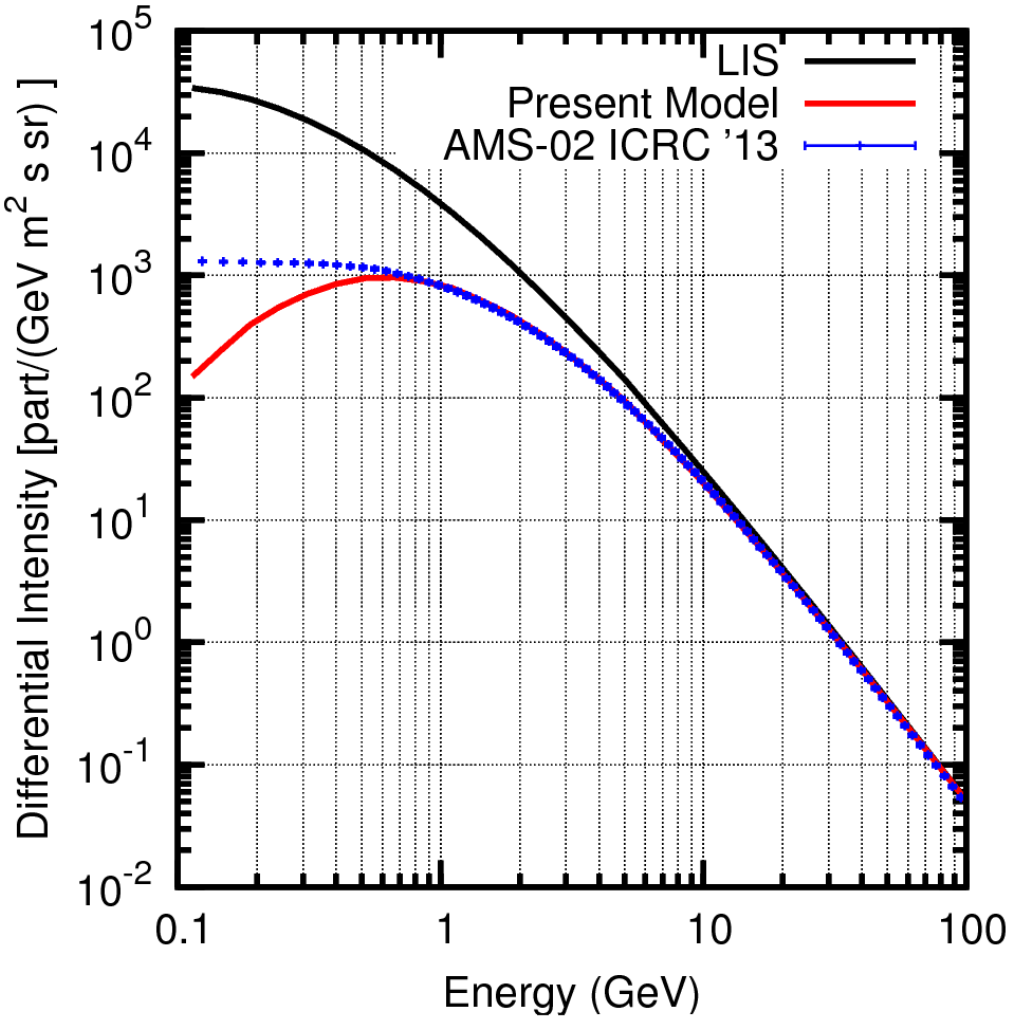


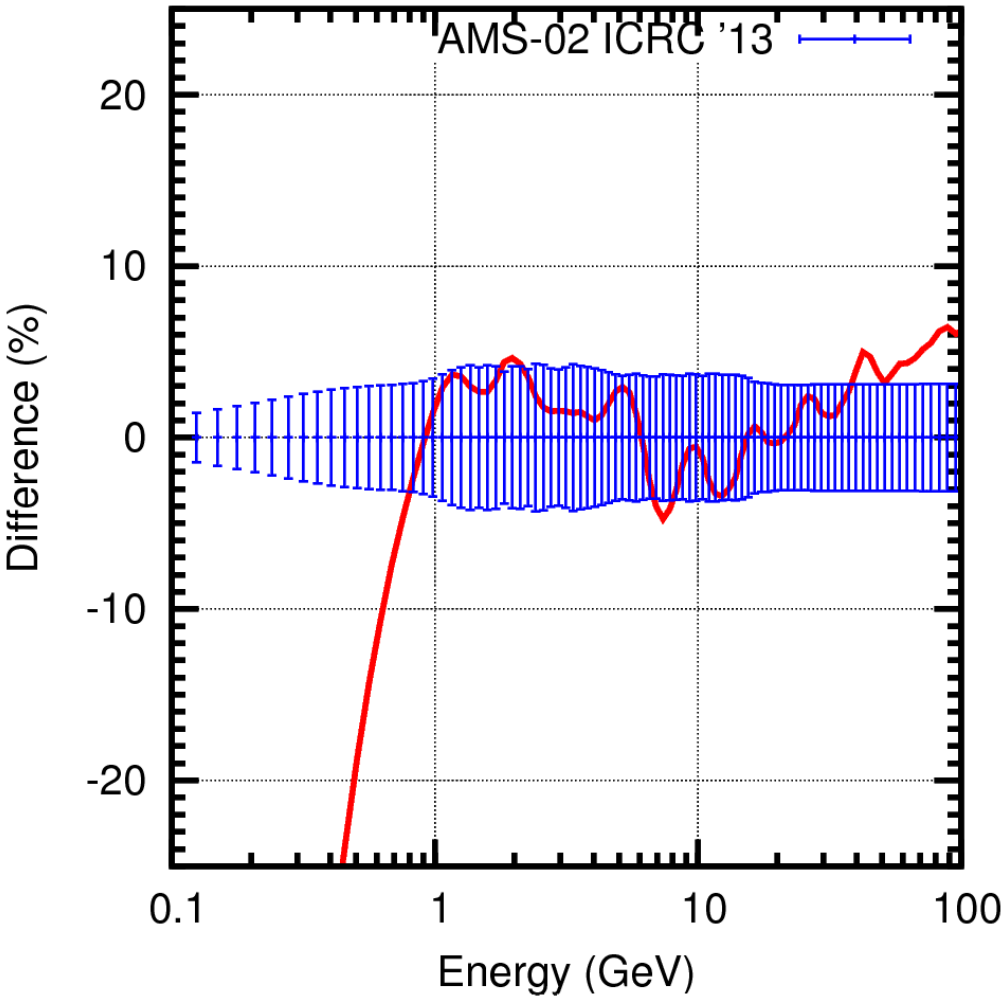
Figure 2: Latitudinal relative intensity along the Ulysses orbit, obtained at different solar co-latitude for proton and electron with particle rigidity 1.7 GV. Intensity are divided by the solution at Earth orbit at the same time, then normalized to the average values at south pole. Solutions with $A < 0$ IMF are evaluated during the Ulysses *fast scan* in 2007.

ICRC 2013 : arXiv:1307.5199

Results

AMS 02 vs. HelMod





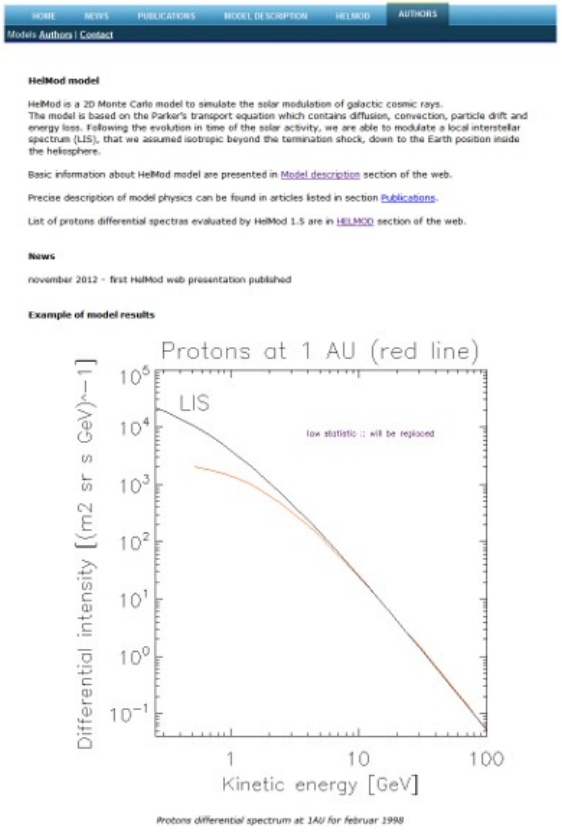
- over 2 years average

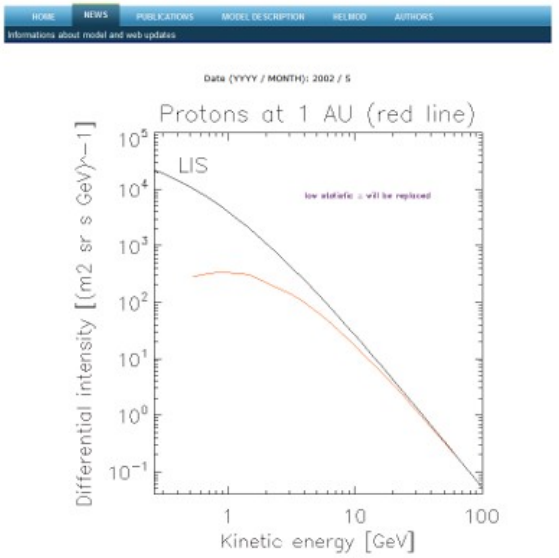
HelMod (v2.01) precision

- Over ~500 MeV (- 800 MeV) good agreement with experiments
- Why not for lower energies?
  - Possible influence of couple of effects
    - ? heliosheath modulation
    - ? shape of heliosphere (tail, north-south asymmetry)
    - ?? some small anisotropy of GCR entering heliosphere ?
    - ? TS acceleration (not included in HelMod actually)
    - ? LIS
    - ? ...

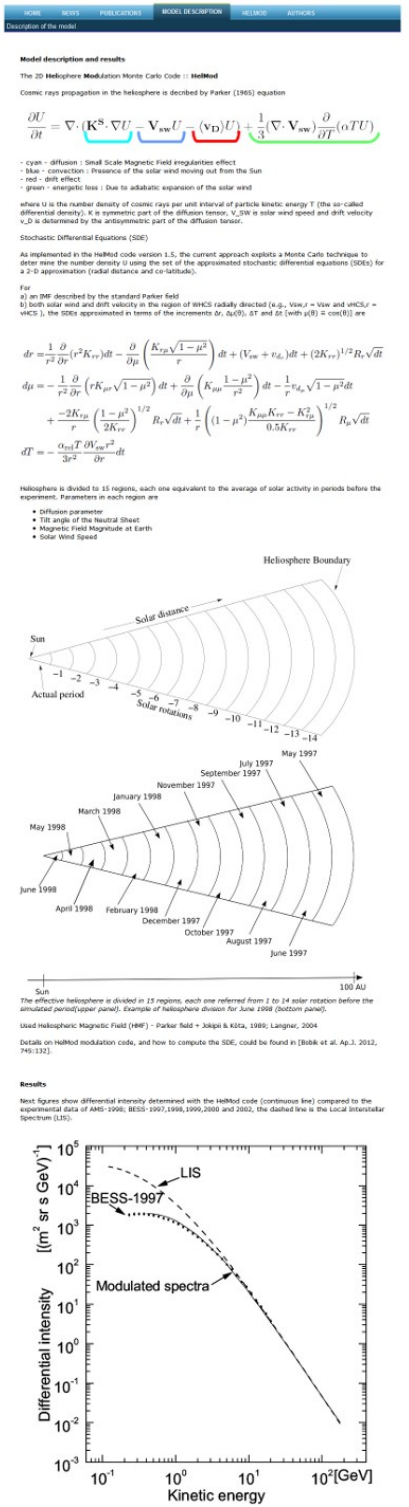
HelMod - www.helmod.org

- Web version of model (ver. HelMod 1.5 / 2.01)
- Model description + bibliography
- Spectra of protons at 1AU catalog from 1990 till 2007



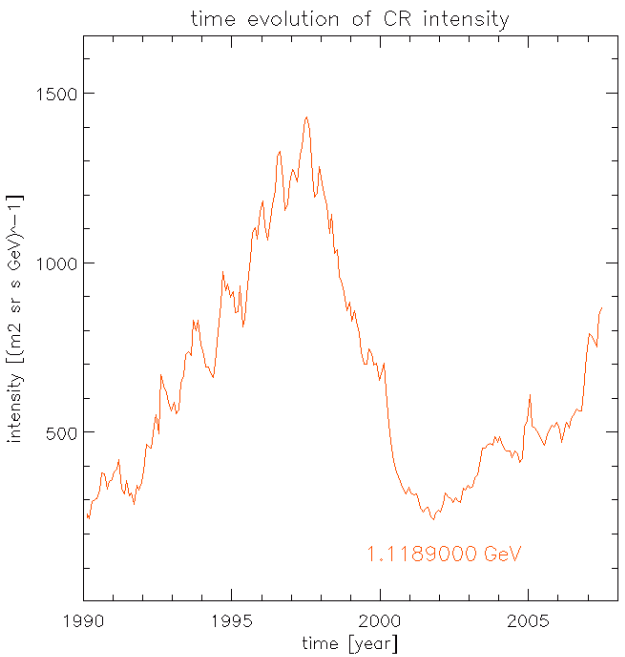


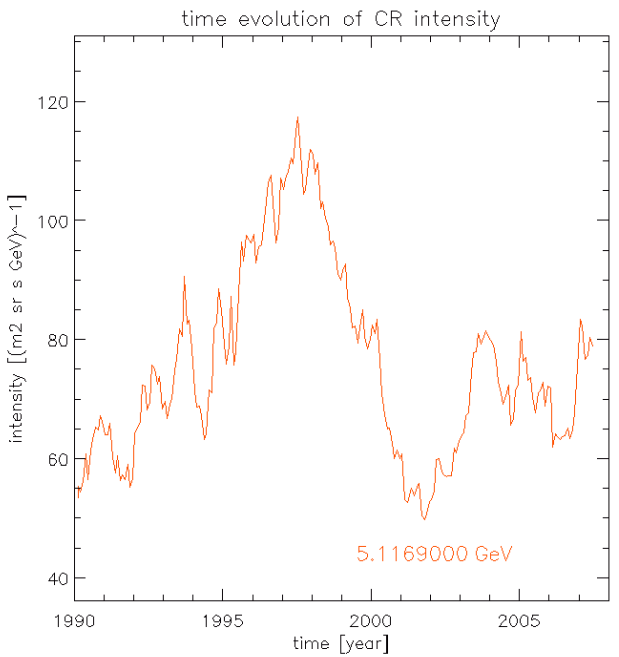
Energy [GeV]	Diff. intensity [(m2 sr s GeV)^-1]	LIS [(m2 sr s GeV)^-1]
177.6186	0.0105	0.0107
137.8650	0.0222	0.0215
107.0089	0.0439	0.0433
83.0587	0.0858	0.0869
64.4690	0.1717	0.1742
50.0399	0.3325	0.3483
38.8403	0.6397	0.6942
30.1473	1.2078	1.3784
23.3999	2.3211	2.7232
18.1627	4.2823	5.3469
14.0976	7.6411	10.4185
10.9424	13.5225	20.1120
8.4933	24.0259	38.3911
6.5924	39.5983	72.3155
5.1169	65.2959	137.3642
3.9717	99.4210	245.7704
3.0828	142.2550	432.0560
2.3928	182.4132	744.2234
1.8573	238.4335	1251.3730
1.4416	307.7300	2045.8280
1.1189	327.6534	3240.3100
0.8685	346.4827	4957.4350
0.6741	318.5697	7309.6090
0.5232	279.6039	10369.0400

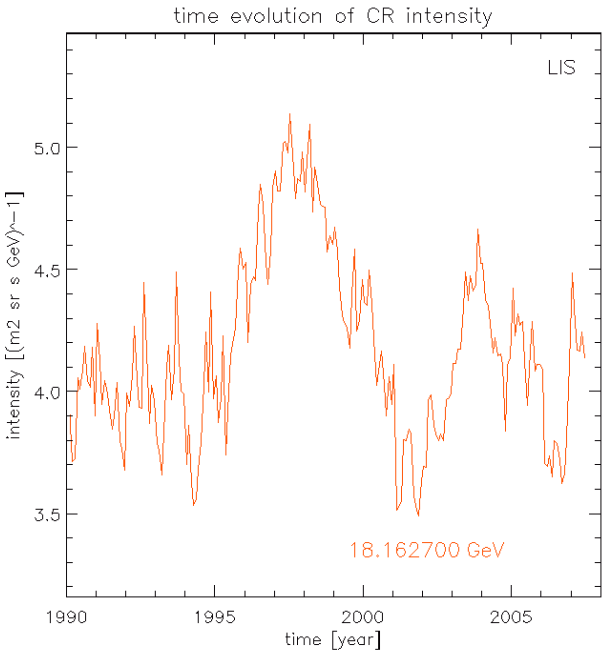


HelMod - www.helmod.org

- in catalog : modulation of different energies during solar cycle







HelMod online[beta] - www.helmod.org

HelMod online – beta version
- already open to use

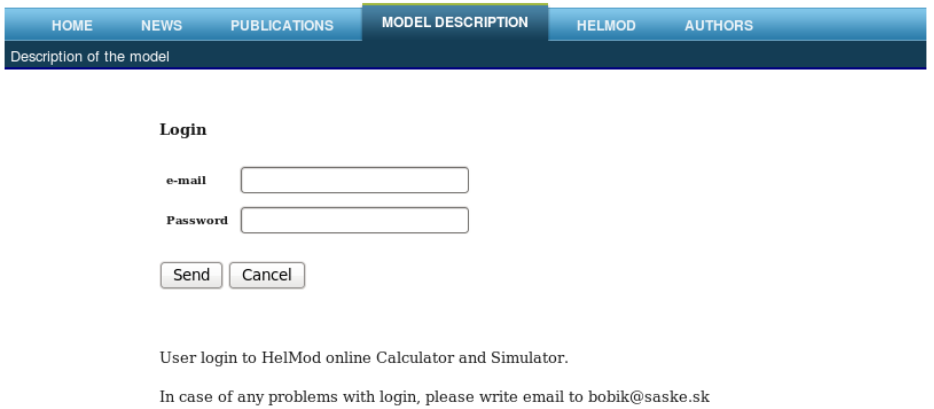
- after registration
at http://www.helmod.org/online

- and Login
at http://www.helmod.org/online/prihlasenie.php

User can use

- HelMod Calculator
  - to find intensity of protons at 1AU for different LIS
  - **fast**

- HelMod Simulator
  - HelMod v2.01 run
  - to evaluate spectrum of protons, antiprotons, electrons, positrons at any distance from the Sun, with the possibility to define LIS by the user
  - **long/overnight** simulation with results received ~12 hours after submitting the job



HelMod online beta - www.helmod.org

Calculator

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Informations about model and web updates

HelMod model online - fast Calculator

Set date and paste your LIS (see description bellow form) to obtain proton modulated spectrum at 1AU.

Year / month 1990 1

Local Interstellar Spectrum

Send Cancel

Local Interstellar Spectrum (LIS)
- two columns structure, first column energy in GeV, second protons intensity in whatever units you want (typicaly (m2 sr s GeV)^-1) - results appear in same units
- columns separated by one or couple blank spaces
- decimal mark in LIS numbers should be dot i.e. 12.34 not comma i.e. 12,34
- LIS example

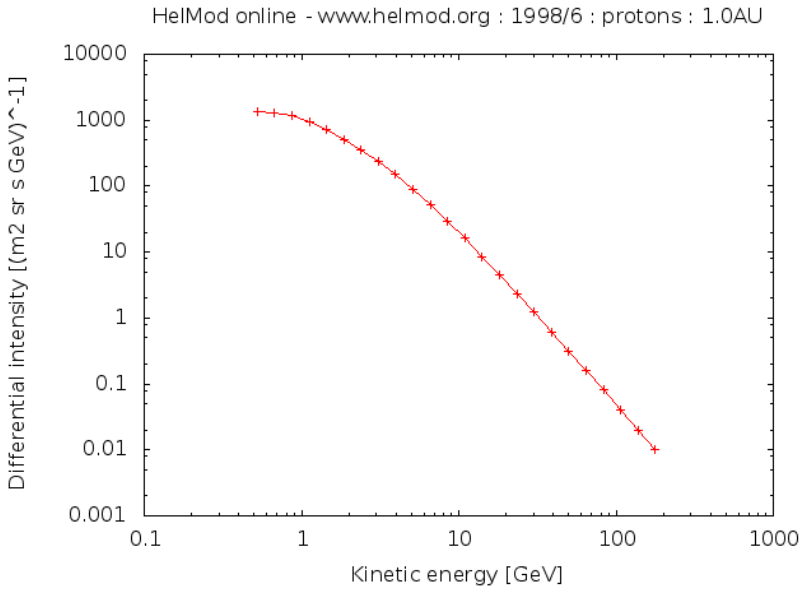
Notes
- version HelMod 1.5

In case of any problems with (or coments to) Calculator, please write email to bobik@saske.sk

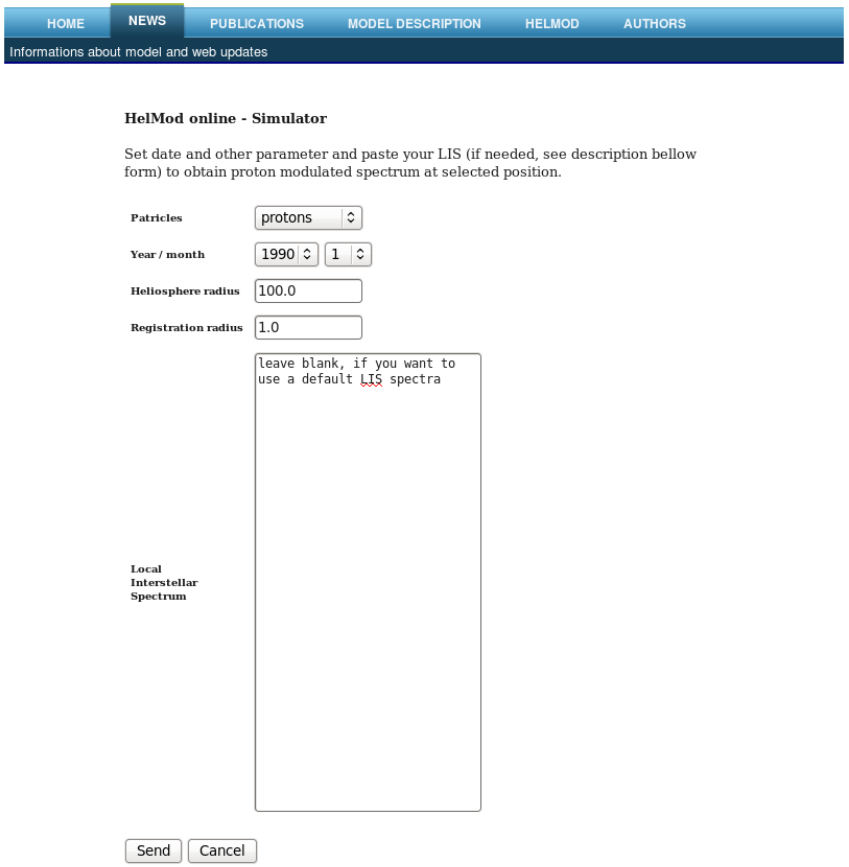
```
columns : Tkin [GeV]    TF    TF*LIS     LIS
- TF is transmission function, for protons at 1AU
- TF*LIS is proton spectrum at 1AU here

    0.1192     0.0053       67.7213    12678.5000
    0.1311     0.0057       70.5267    12313.6000
    0.1442     0.0062       73.3831    11927.8000
    0.1586     0.0065       74.3708    11523.4000
    0.1745     0.0067       74.7600    11102.3000
    0.1919     0.0071       75.7042    10667.0000
    0.2111     0.0080       81.3534    10219.2000
    0.2323     0.0089       86.9796     9760.9300
    0.2555     0.0099       91.5993     9293.9400
    0.2810     0.0108       94.9730     8819.9000
    0.3091     0.0118       98.1758     8340.1000
    0.3400     0.0125       98.4294     7857.5700
    0.3740     0.0133       97.8007     7373.9200
    0.4114     0.0143       98.5490     6890.8800
    0.4526     0.0170      108.7061     6410.0300
    0.4979     0.0199      117.9599     5933.0500
    0.5476     0.0241      131.6866     5461.7800
    0.6024     0.0299      149.5725     4998.7200
    0.6626     0.0363      165.1441     4547.5600
    0.7289     0.0433      178.0079     4113.0500
    0.8018     0.0509      188.3917     3699.5100
    0.8820     0.0593      196.1926     3309.3900
    0.9702     0.0682      200.7864     2943.5200
    1.0672     0.0780      203.0711     2602.2900
    1.1739     0.0897      205.1407     2285.9900
    1.2913     0.1035      206.5526     1994.9000
    1.4204     0.1187      205.2800     1729.0700
    1.5625     0.1373      204.2952     1488.3100
    1.7187     0.1580      201.0206     1272.1200
    1.8906     0.1793      193.6080     1079.7000
    2.0797     0.1957      178.1247      910.0040
    2.2876     0.2138      162.8596      761.7120
    2.5164     0.2354      149.0929      633.3130
    2.7680     0.2608      136.4487      523.1650
    3.0448     0.2888      124.0279      429.5310
    3.3493     0.3105      108.8866      350.6410
    3.6842     0.3331       94.8499      284.7510
    4.0526     0.3574       82.2721      230.1660
    4.4579     0.3824       70.8571      185.2950
    4.9037     0.4099       60.9330      148.6710
    5.3941     0.4370       51.9872      118.9650
    5.9335     0.4643       44.1045       94.9965
    6.5268     0.4943       37.4341       75.7344
    7.1795     0.5273       31.7883       60.2828
    7.8975     0.5637       26.9779       47.8615
    8.6872     0.5995       22.6166       37.7284
    9.5559     0.6247       18.4554       29.5447
   10.5115     0.6524       15.0225       23.0272
   11.5627     0.6822       12.1985       17.8816
   12.7190     0.7144        9.8919       13.8458
   13.9908     0.7499        8.0218       10.6971
   15.3899     0.7657        6.3179        8.2508
   16.9289     0.7810        4.9648        6.3567
   18.6218     0.7964        3.8976        4.8938
   20.4840     0.8092        3.0475        3.7661
   22.5324     0.8232        2.3856        2.8979
```

HelMod online[beta] - www.helmod.org

Simulator

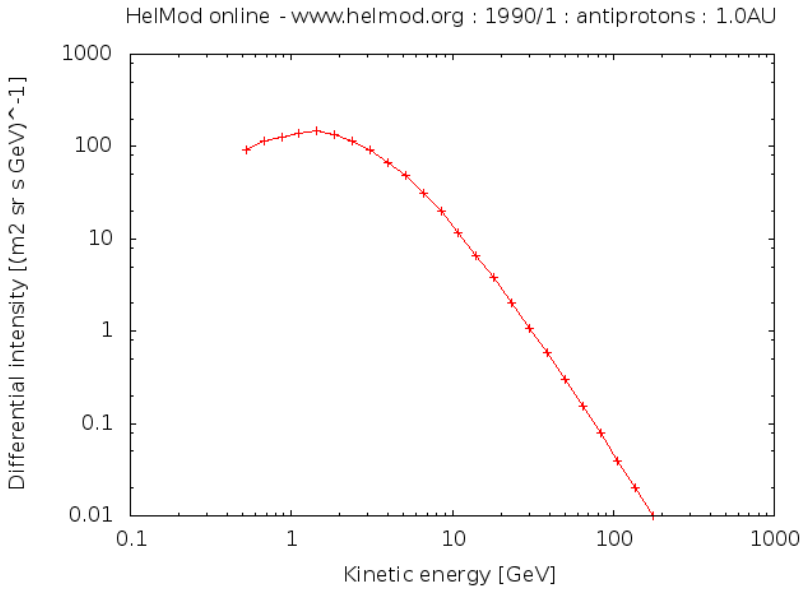



```
protons  1998/ 6  :: Heliosphere radius 100.0
Energy [GeV]   flux at   1.0 AU [(m2 sr s GeV)^-1]   LIS [(m2 sr s GeV)^-1]
    177.619        0.0099953         0.0098227
    137.865        0.0199230         0.0197832
    107.009        0.0405625         0.0397962
     83.059        0.0815655         0.0799322
     64.469        0.1608124         0.1602340
     50.040        0.3166453         0.3204130
     38.840        0.6154839         0.6387043
     30.147        1.2421106         1.2681400
     23.400        2.3608598         2.5053863
     18.163        4.4933914         4.9191811
     14.098        8.5051037         9.5850108
     10.942       16.1028095        18.5030492
      8.493       29.0926088        35.3198396
      6.592       52.6369888        66.5302508
      5.117       90.9505175       126.3750640
      3.972      149.9040432       226.1087680
      3.083      235.0741932       397.4915200
      2.393      359.5468115       684.6855280
      1.857      500.6274990      1151.2631600
      1.442      725.7985585      1882.1617600
      1.119      925.1699185      2981.0852000
      0.868     1157.1810066      4560.8402000
      0.674     1286.4726383      6724.8402800
      0.523     1360.8011098      9539.5168000
```



HelMod online beta - www.helmod.org

Results



antiprotons 1990/ 1 :: Heliosphere radius 100.0

Energy [GeV]	flux at 1.0 AU [(m2 sr s GeV)^-1]	LIS [(m2 sr s GeV)^-1]
177.619	0.0100568	0.0098227
137.865	0.0200075	0.0197832
107.009	0.0397349	0.0397962
83.059	0.0798586	0.0799322
64.469	0.1542865	0.1602340
50.040	0.2996537	0.3204130
38.840	0.5833482	0.6387043
30.147	1.0825520	1.2681400
23.400	2.0583720	2.5053863
18.163	3.8664622	4.9191811
14.098	6.5900416	9.5850108
10.942	11.5509421	18.5030492
8.493	19.7703572	35.3198396
6.592	31.2718412	66.5302508
5.117	48.0507740	126.3750640
3.972	66.2152513	226.1087680
3.083	90.9432873	397.4915200
2.393	114.6981774	684.6855280
1.857	135.0833151	1151.2631600
1.442	148.3566701	1882.1617600
1.119	138.9295140	2981.0852000
0.868	125.7635301	4560.8402000
0.674	114.7573105	6724.8402800
0.523	91.5407725	9539.5168000

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Calculator results

Columns in the list:
- job id (identification)
- period selected for simulation
- link to file with user LIS
- link to file with evaluated spectrum

job id: 1 :: 1990/1 :: LIS file :: Results

Simulator results

Columns in the list:
- job id (identification)
- period selected for simulation
- link to file with evaluated spectrum
- figure of evaluated spectrum
- time when job was submited to the system

job id: 1 :: 1990/1 :: Results :: Figure :: Sun Aug 18 17:39:48 CEST 2013
job id: 2 :: 1990/1 :: Results :: Figure :: Sun Aug 18 17:40:01 CEST 2013
job id: 4 :: 1990/1 :: Results :: Figure :: Mon Aug 19 18:21:45 CEST 2013
job id: 5 :: 1990/1 :: Results :: Figure :: Tue Aug 20 11:06:23 CEST 2013
job id: 6 :: 1998/6 :: Results :: Figure :: Tue Aug 20 16:11:50 CEST 2013

Results in simulator list appear only for already finished jobs. If results do not appear more that 12 hours after submission, we apologize, but we are probably overloaded by number of tasks from other HelMod online simulator users.

HelMod online[beta] - www.helmod.org

Further development

- **Soon - i.e. september/october 2013**
  - Results from Simulator for all heliolatitudes
  - Calculator update to HelMod version 2.01
- **End of this year**
  - Advanced Simulator
    - User can set a couple of additional simulation parameters
    - Ratio between perpendicular and parallel diffusion coefficient
    - Fast solar wind speed
    - Ect.
- **Later**
  - Add ^{3}He or ^{4}He to HelMod online

Register at *http://www.helmod.org/online*

and Login / use HelMod at
http://www.helmod.org/online/prihlasenie.php

Thank you for your attention

This work was supported by VEGA grant agency project 2/0076/13.