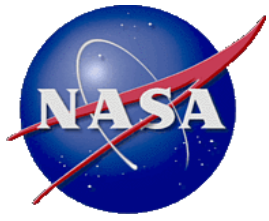**National Aeronautics & Space Administration**

Johnson Space Center

Environments Models used for Hardware Certification & BON GCR Model Status

Brandon Reddell/Pat O'Neill
NASA JSC Engineering Directorate
Avionic Systems Division
Electronic Design & Manufacturing Branch

Space Environment Engineering
and Science Applications Workshop
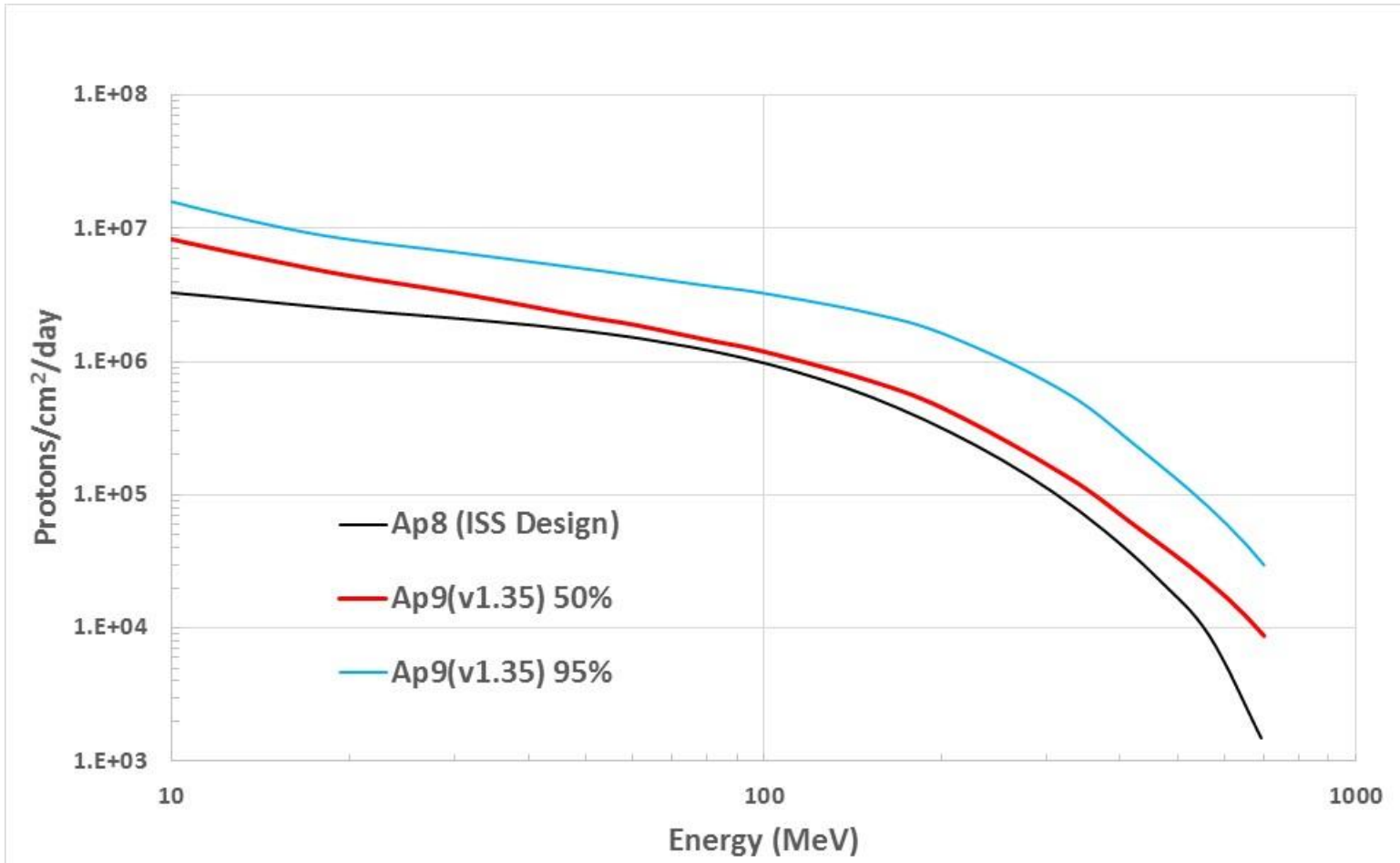Boulder, CO, September 2017

Environments & Models

1. LEO – trapped protons – currently using Ap8, evaluating Ap9

2. Solar Particle Events – currently use CREME96 October 1989 Event

3. Galactic Cosmic Rays – primarily use Badhwar-O'Neill model (BON), some use of Nymmik model (as part of the CREME96 tool)
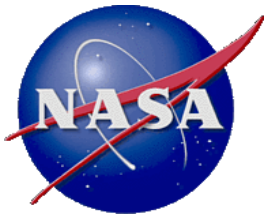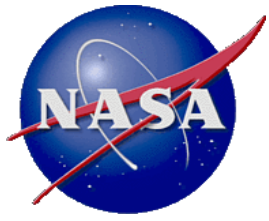
500 km x 500 km 51.6º ISS Design Orbit
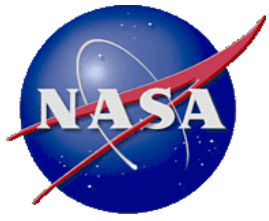
LEO Missions

- We currently use Ap8 models for environment definition and for hardware rate analyses.
- Biggest issue here – Ap9 appears to be significantly higher than Ap8
    * rates may be higher, doses will be higher
- Is the Ap9 data more accurate?
- Our understanding is that there is no data in this region.
- Generally, not a major issue since:
    * Not worried about dose
   ** Rates are usually dominated by GCR

NASA Human Spaceflight is focused on Beyond LEO

- Environments of Concern (for both Crew and Hardware)
    - Solar Particle Events (SPE)
        - A huge driver for crew dose, and hardware soft error rates
    - Galactic Cosmic Radiation (GCR)
        - Very important for astronaut radiation risk calculations
        - For hardware – the driving environment for single event effects
- What is needed?
    - SPE's: Ability to define appropriate (more realistic) solar particle events for short duration missions at various times in the solar cycle
    - GCR's: Updated models to account for more recent satellite data as well as the ability to make predictions anywhere in the heliosphere

Badhwar-O'Neill GCR Model History

- <1996 – Model introduced to provide improved crew dose and computer upset rates for the Space Shuttle program
    - GCR transport modelled through diffusion-convection theory
    - Provides a 1D steady-state Fokker-Planck solution, with parameters fit to Neutron Climax data and sunspot data
    - Provided a significant improvement to the MSU and CRÈME models
- 2005 – updated fits using the ACE GCR measurement data
- 2010 – updated fits, used ISS# for solar modulation
- 2014 – updated fits to include more GCR data from other satellites and balloon data (including AMS, Pamela, and IMAX data)
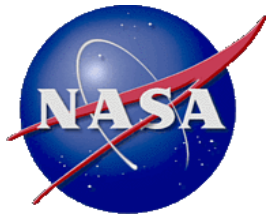
# The Heliosphere is Very Complex (and it's big too, 100 AU)

solar magnetic field & solar wind features
- 100 AU
- open & closed field lines
- 22 year cycle starts at solar max (B=0)
- 11 year sunspot cycle starts at solar min
- sun rotation rate depends on latitude
- sunspots start at high lat, move to low
- CME's start low, move high

GCR's from Milky Way encounter the heliosphere:
- the large scale magnetic field carried by steady solar wind
- local field carried by events (SS & CME)

GCR's

GCR's
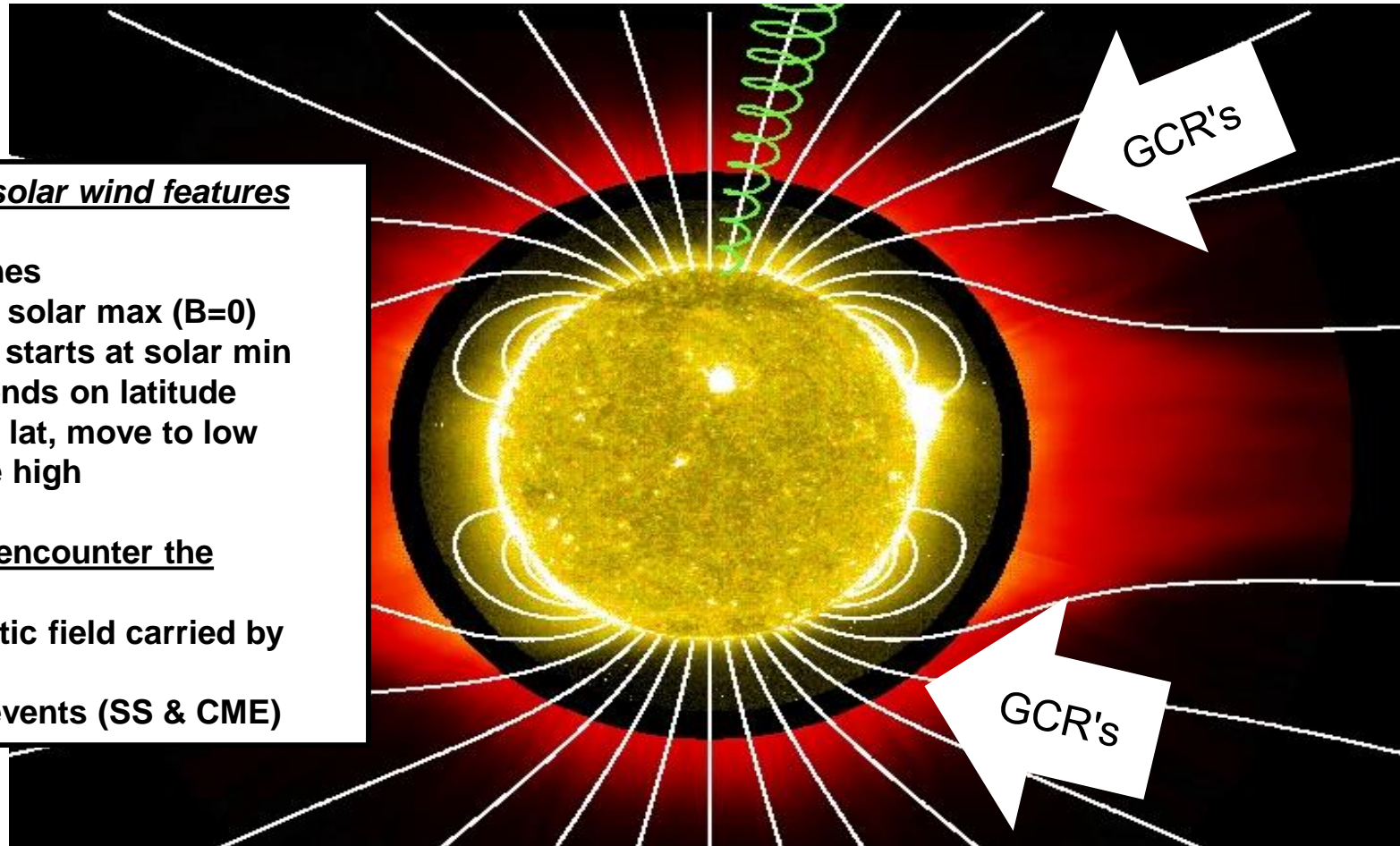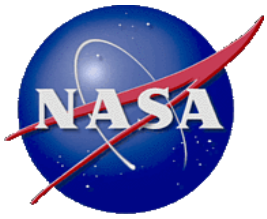
Fokker-Planck Equation - time dependent and 3-D

$$\frac{\partial f}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\kappa_{rr}\frac{\partial f}{\partial r}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\kappa_{\theta\theta}\sin\theta\frac{\partial f}{\partial\theta}\right) + \frac{1}{r^2\sin^2\theta}\frac{\partial}{\partial\phi}$$

$$\cdot\left(\kappa_{\phi\phi}\frac{\partial f}{\partial\phi}\right) + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 V)\frac{\partial}{\partial p^3}(p^3 f) - \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 V f)$$

Fokker-Planck equation - governs GCR <u>flow</u> in & out of the Sun's magnetic field (heliosphere = 0 to 100 AU)
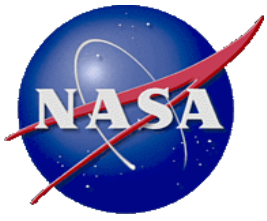
There's <u>1 time term </u>(It's time dependent), <u>3 diffusion (k) terms </u>(1 radial and 2 angular, its 3-D), <u>1 energy loss term </u>(p is momentum) and <u>1 solar wind (V) term </u>(called drift or convection)

It gives the energy spectrum (flux f vs ion momentum) for each GCR ion

Solve it at every point (i.e. radius from sun, theta=θ, phi=ϕ) in the heliosphere then you will know the GCR flux spectrum f(p, r, theta, phi) everywhere from the sun out to r=100 AU at all times over the solar cycle

You must know the diffusion coefficients (they depend on #sunspots), the solar wind velocity (V=450 km/s) and the constant flux at the outer boundary - the Local Interstellar Spectrum (LIS)

You have to fit these parameters so f matches the GCR measurements from ACE, PAMELA, …

# FOKKER-PLANCK ACCOUNTS FOR FLUX REDUCTION DUE TO SOLAR MODULATION

For each element (like hydrogen, …, carbon,… iron) the blue line (flux at 100 AU) is the Local Interstellar Spectrum (LIS) - IT'S CONSTANT - IT'S IN THE MILKY WAY - IT DOESN'T CHANGE

Fokker-Planck solution (green dashed line) matches the GCR measurement (say ACE etc.) at some time at r=1 AU (theta & phi = 0) because we adjusted krr, V, & the LIS

The flux spectrum is lower at 1 AU because the sun's magnetic field modulates the flux as it diffuses inward & it shifts to left due to energy loss
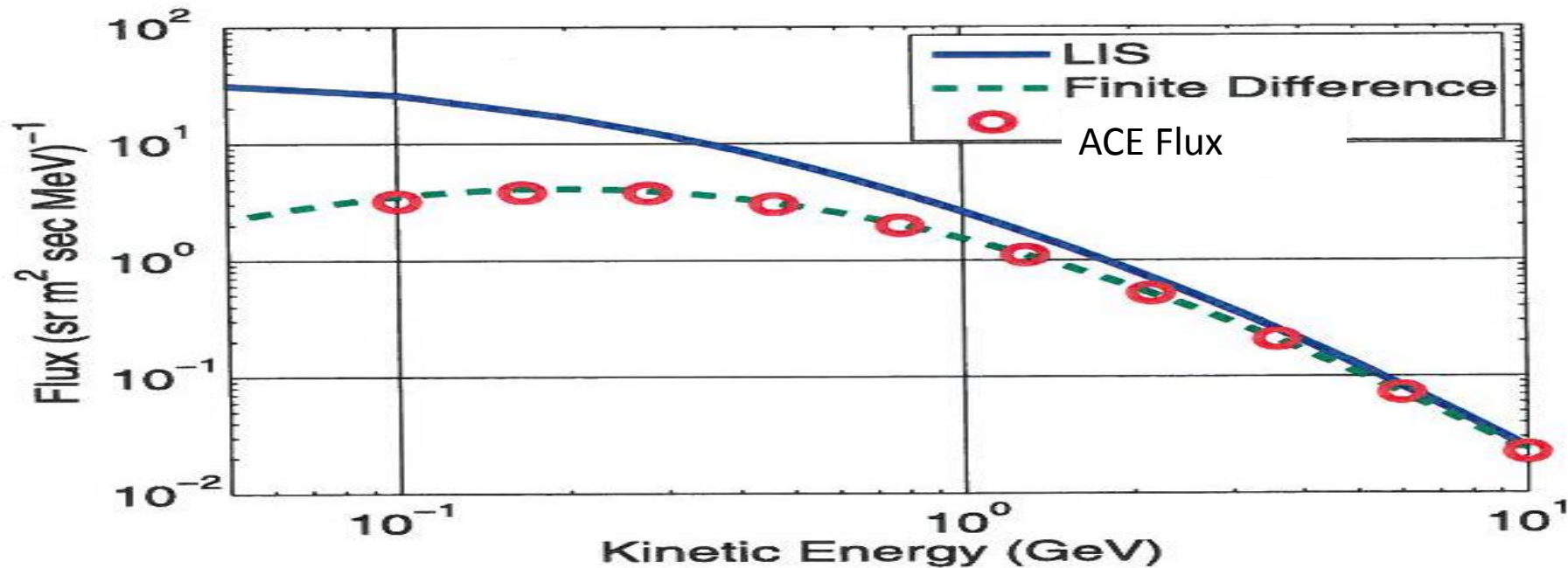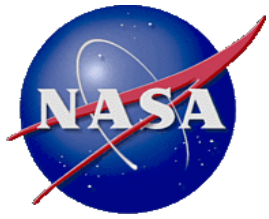
BO Model's Fokker-Planck is easy to solve,
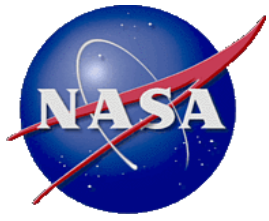# It's steady state (left hand side is 0) and 1D (r)

$$0 = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \kappa_{rr}\frac{\partial f}{\partial r}\right) +$$

$$+ \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 V)\frac{\partial}{\partial p^3}(p^3 f) - \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 V f)$$
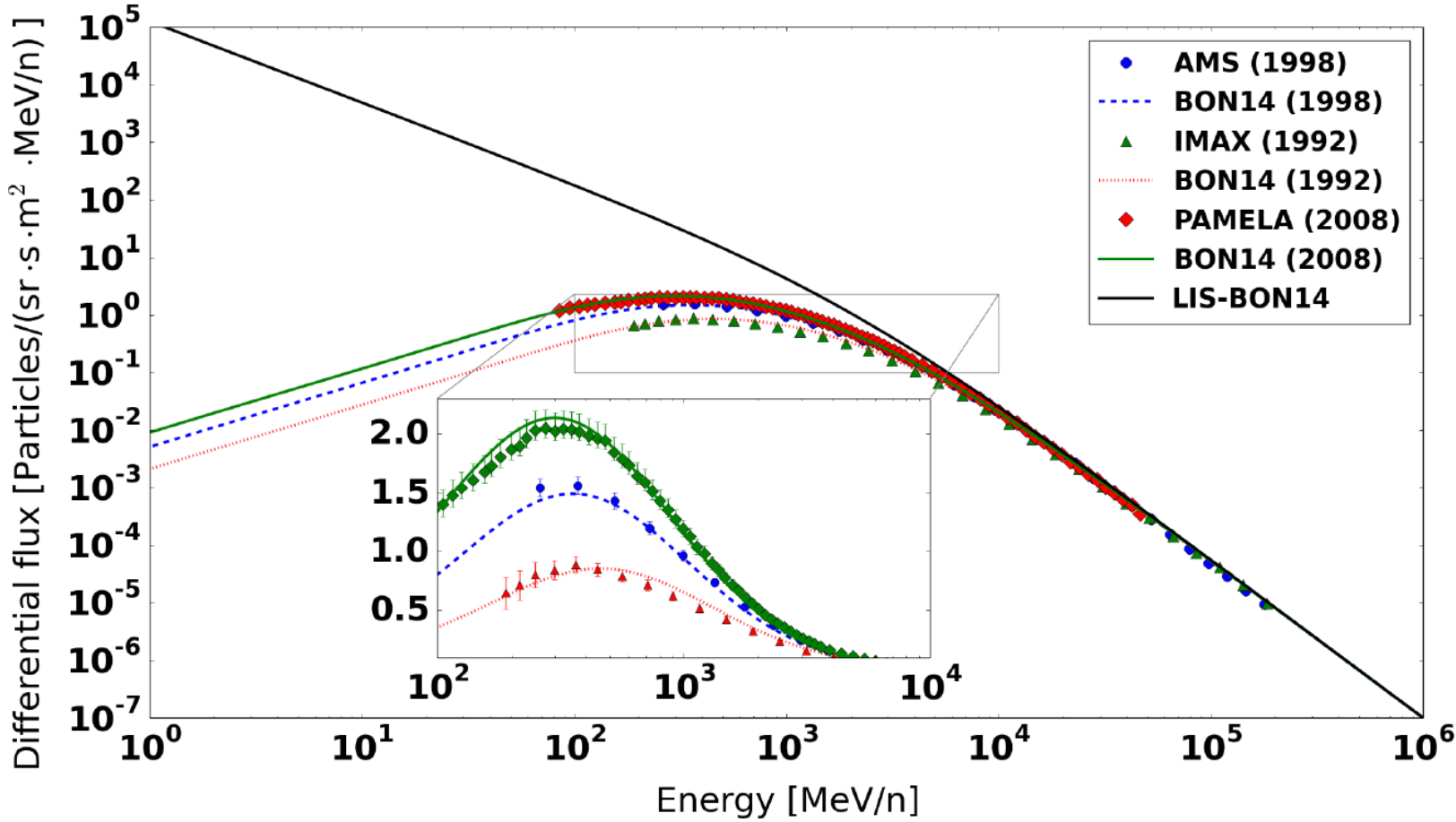
Now, Only 3 terms left

1. diffusion inward depends on Krr - which depends on # sun spots

2. loss of energy as GCR diffuse inward (p is momentum)

3. outward convection (drift) of solar wind (V)

This is Easy to solve using Finite Difference method

However, it is very difficult to solve by Finite Differencing if you add time & another dimension (see chart #7), currently investigating other techniques.
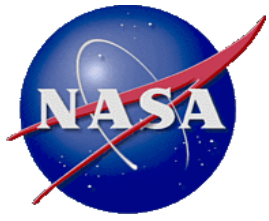
BON14 vs. Data

Legend:
- AMS (1998)
- BON14 (1998)
- IMAX (1992)
- BON14 (1992)
- PAMELA (2008)
- BON14 (2008)
- LIS-BON14

$$Rd = \frac{1}{N} \sum_{k=1}^{N} \frac{Model_k - Data_k}{Data_k}$$

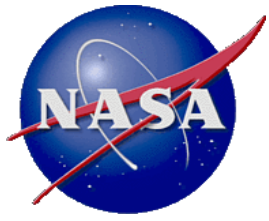$$|Rd| = \frac{1}{N} \sum_{k=1}^{N} \frac{|Model_k - Data_k|}{Data_k}$$

	Average [%]	
	Rd	$|Rd|$
BON11	17.9	23.7
BON14	-0.4	13.0

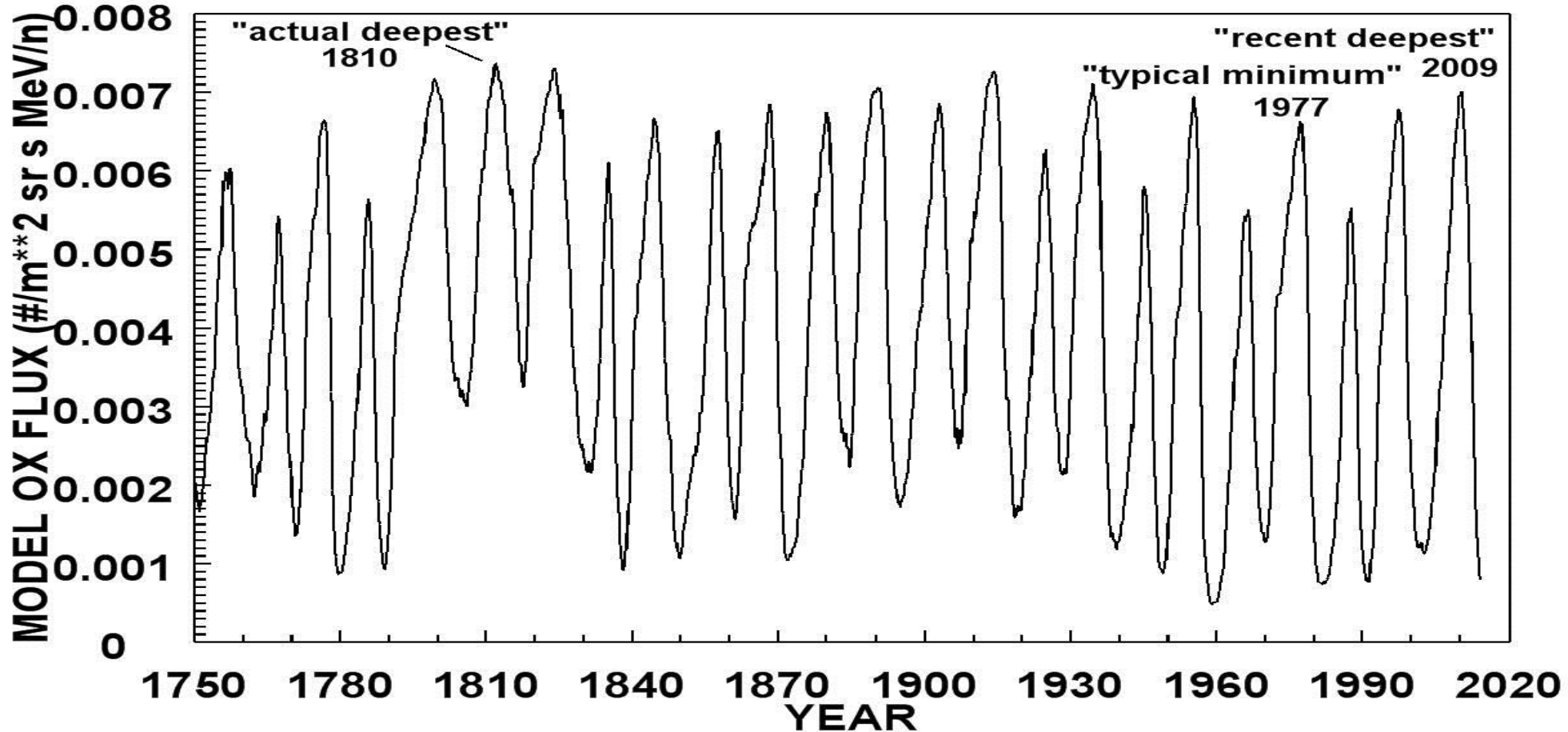# Why should we add time and another dimension?

**At Solar Max, the Sun's Field "flips" - every 11 years
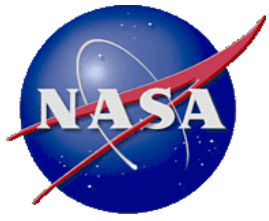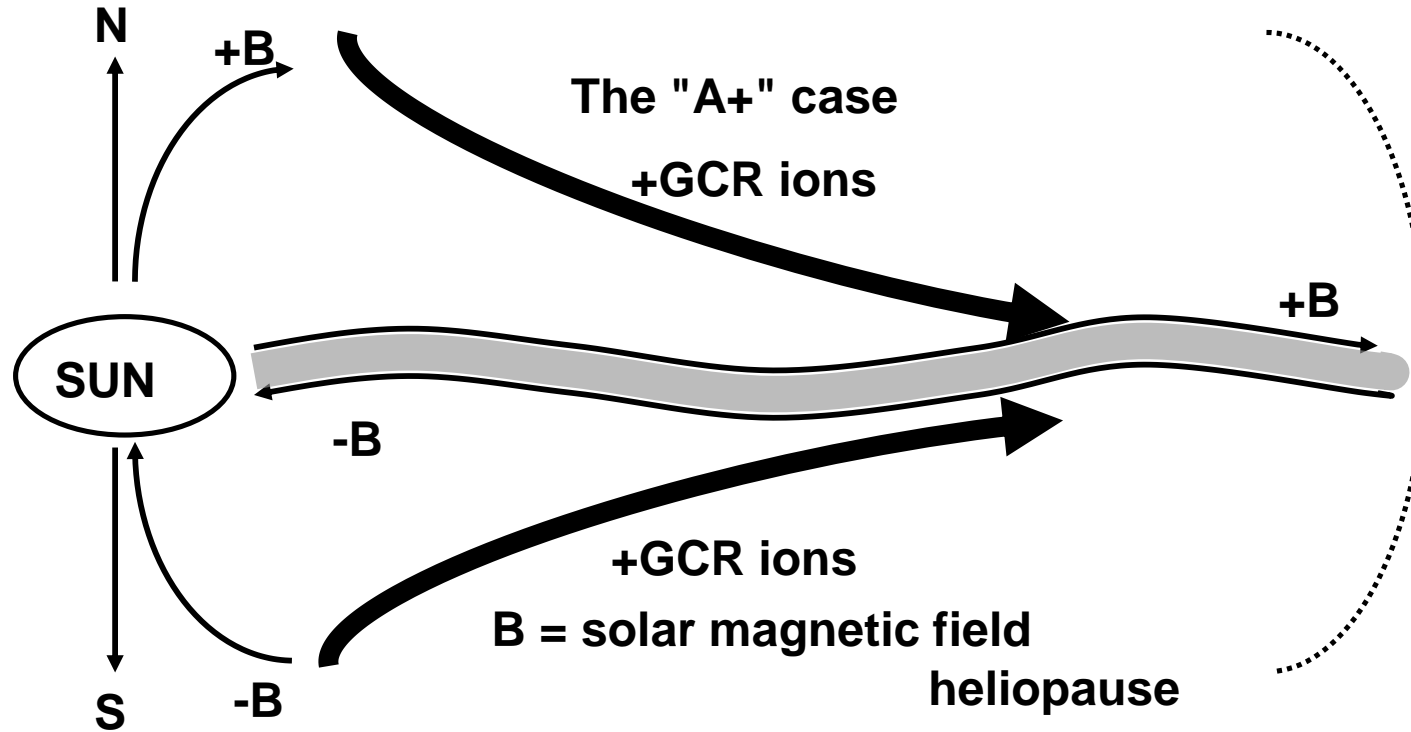The GCR peaks (at A- field) & plateaus (at A+ field)**
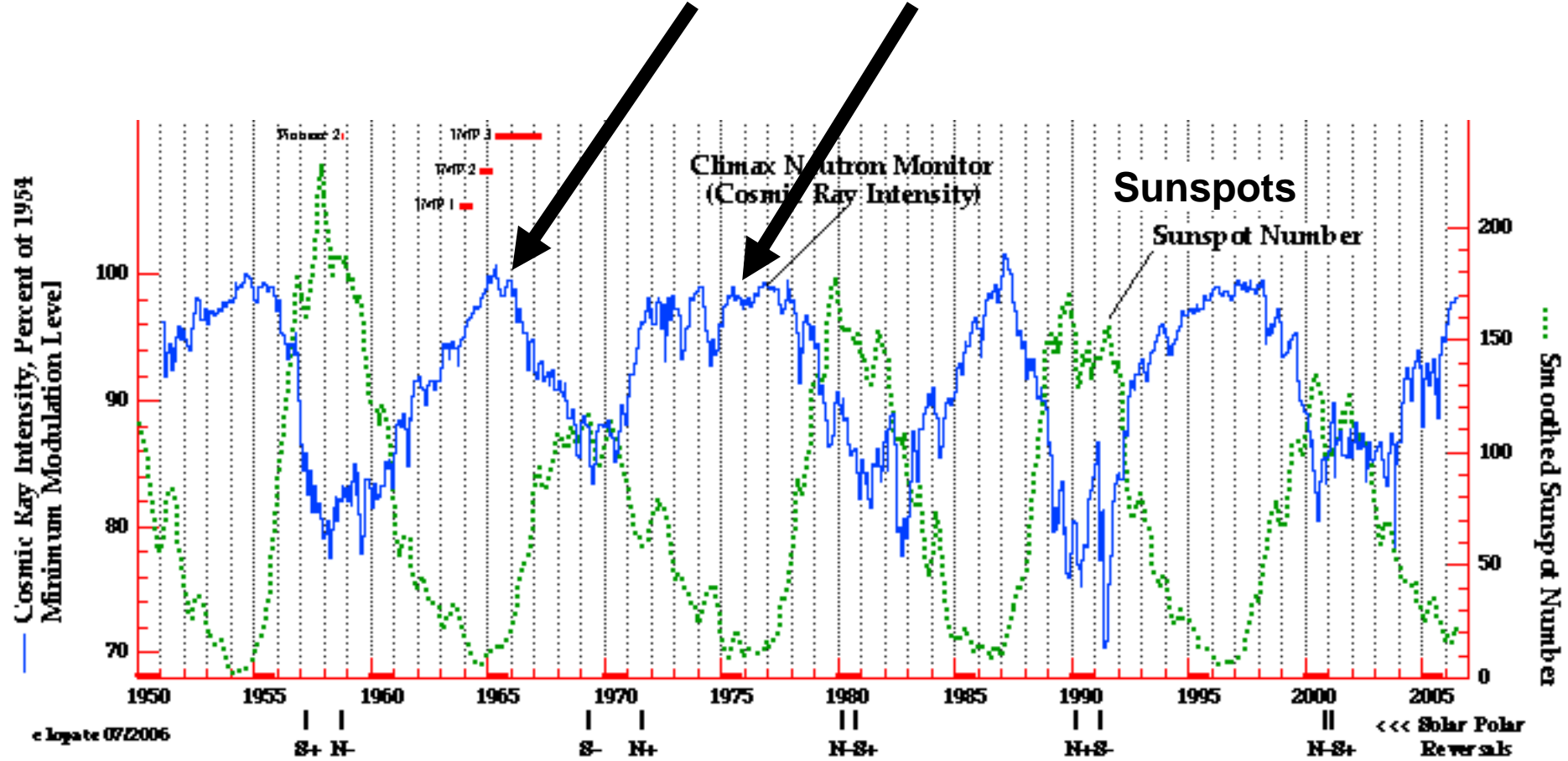
Current BO Model DOES NOT show the "peaks" & "plateaus"

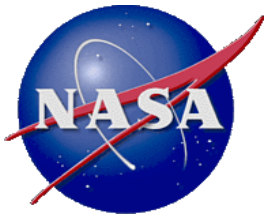**BO Model of GCR Spectra for every solar cycle (1 to 24)**

# GCR's ENTER ALONG THE POLAR AXES WHEN B IS + IN THE NORTHERN HEMISPHERE (A+)

The "A+" case

+GCR ions

N

+B

+B

SUN

-B

+GCR ions

B = solar magnetic field

heliopause

S   -B

Plateau's (A+) have a **RAPID** rise because they have immediate access to Earth

and they have a **DELAYED** decline because they have a long "exit" path

& vis-versa GCR's ENTER ALONG THE EQUATOR WHEN B IS – IN THE NORTHERN HEMISPHERE (A-)

N

-B

The "A-" case

+GCR ions

-B

SUN

+B

+GCR ions
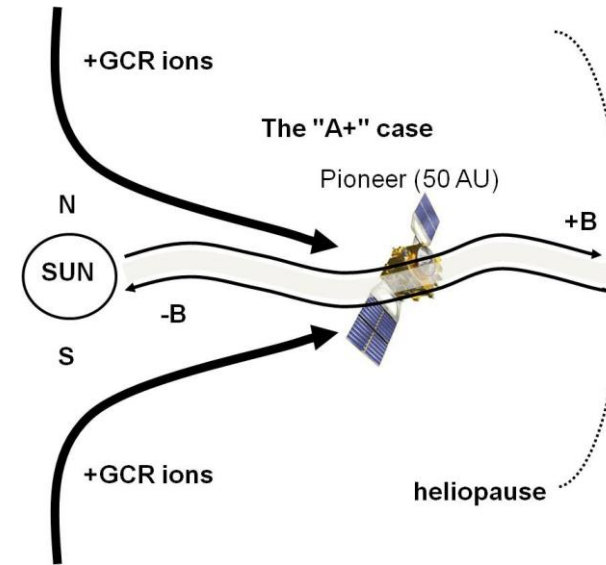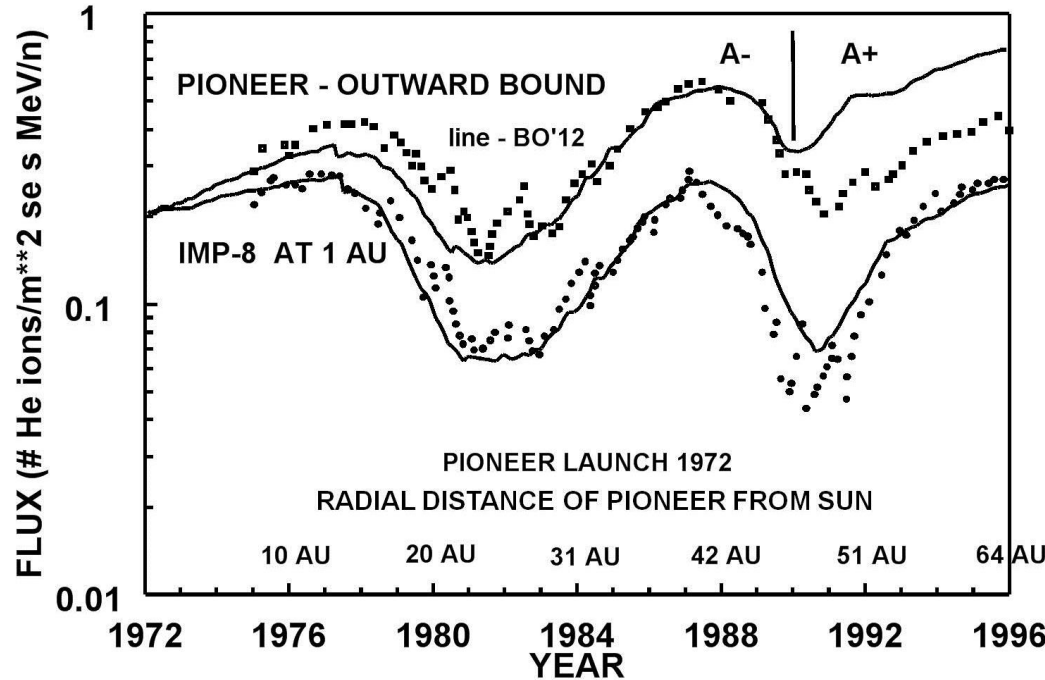
B = solar magnetic field

heliopause

S   +B
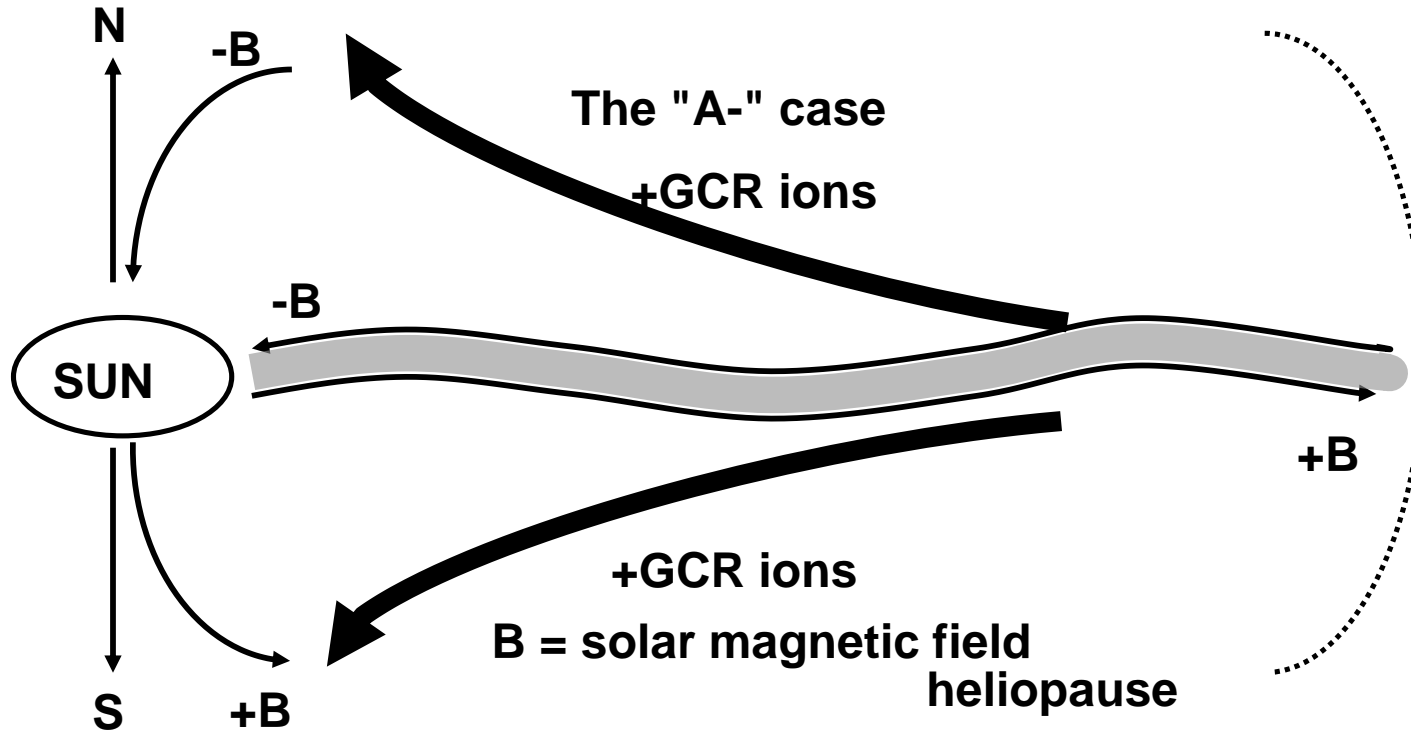
CME's start Solar Cycle (at solar min) at Equator and Move to Higher Latitude

So, Pointed cycles (A-) GCR's entering along the equator are **IMMEDIATELY** modulated
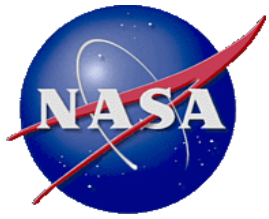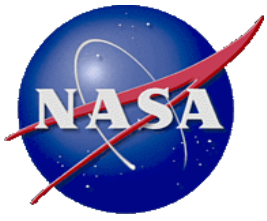
More proof we need "curvature & gradient drift"

Model & Measured GCR Flux disagree on Pioneer ~ 50 AU Deep in 1990

Model assumes the GCR's are mainly coming from the heliopause at 100 AU

But, after the solar field <u>becomes A+ (1990)</u> many <u>GCR's Reach Pioneer the long way</u> by the sun's poles - *"curvature & gradient drift"* ***- and they are more attenuated***

BO doesn't model the modulation for GCR's entering along the solar poles

Summary

- For human space missions:
    - Need a community accepted and accurate prediction of the LEO proton environment
    - Strong desire for a community accepted model to provide a solar-cycle dependent SPE definition in LEO and beyond LEO
    - Efforts to update the Badhwar-O'Neill GCR model
        - First step is to add back in using Neutron Climax Data option (in addition to sunspots)
        - Convert the BON model from a 1D to a 3D model accounting for curvature-gradient drift and add time dependence

Thank You!
Questions?

<u>August, 2017 – Harvey Aftermath – Kayak/Boating Rescue Operations</u>

NASA Road 1, approximately 5-7 miles west of the Johnson Space Center

Here and surrounding neighborhoods 3-5 feet under water.