Acceleration of Anomalous Cosmic Rays:
Solar Cycle Variations

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# Prelude: Motivation

- *The disparity between galactic and anomalous cosmic rays during the past and current solar minima offers new indicate that ACRs were less efficiently accelerated than in previous cycles.*

- *This could happen for a number of reasons: steepening of the source spectrum due to faster diffusion (Moraal & Stoker, 2010); changes in seed particles; and/or shock strength & position, etc*

- *We do not aim for quantitative fit yet, shall focuses on (1) tilt angle and (2) decreasing electrostatic potential (Jokipii 1982, 1996)*

GCRs at record high level in 2009 (Mewaldt et al)

GCRs surge as …
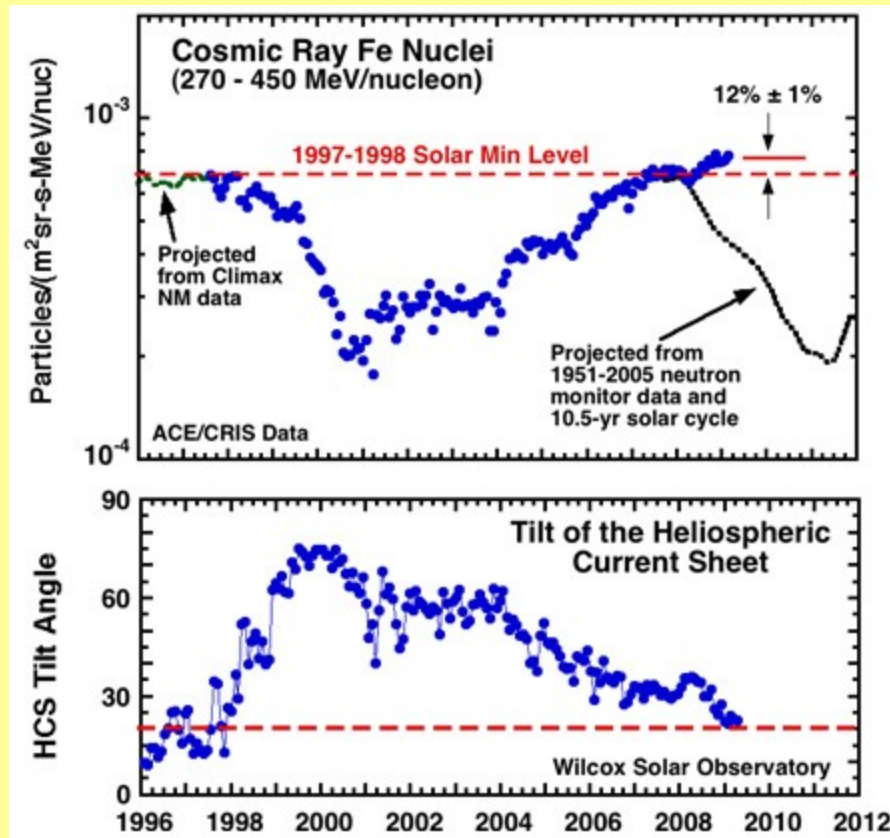
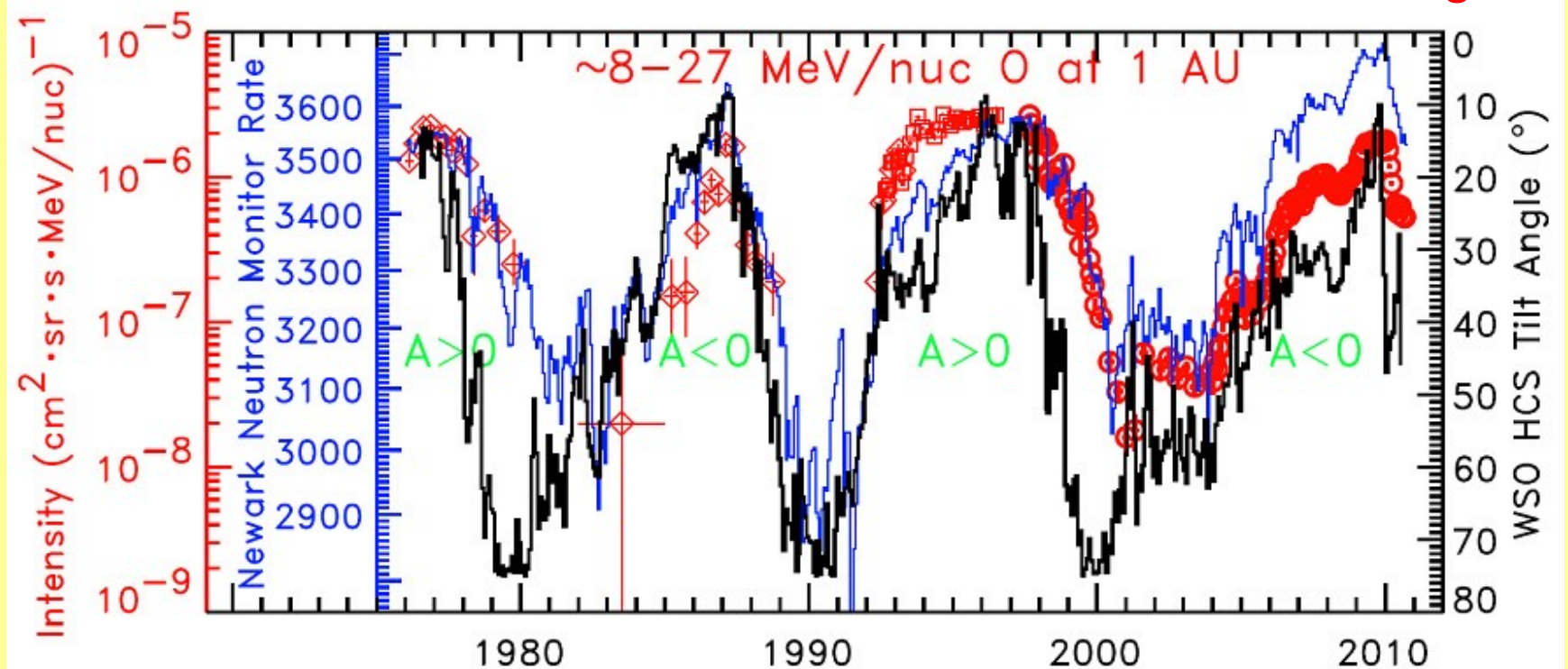270-450 MeV/n Iron at ACE

Black: prediction from earlier cycle

GCR increase is the result of : decreasing B & decreasing tilt ?

…HCS flattens

ACRs in the last 3 solar cycles (from Ace News)

HCS flattens

CR surge

~8-27 MeV/nuc O at 1 AU

A>0   A<0   A>0   A<0

ACRs did not surpass their 1987 level

Last Unusual Solar Minimum

- *Sunspot number low*
- *Magnetic field weakest ever recorded*
- *Solar Wind pressure low*
- *Tilt angle remained moderate until 2008*
  did not flatten as in other minima

- *GCRs at record high level !*
  Neutron Monitors, ACE Iron
- *ACRs track GCRs but did not surpass previous levels*
- *Implication: ACR source intensity was lower at TS ?*
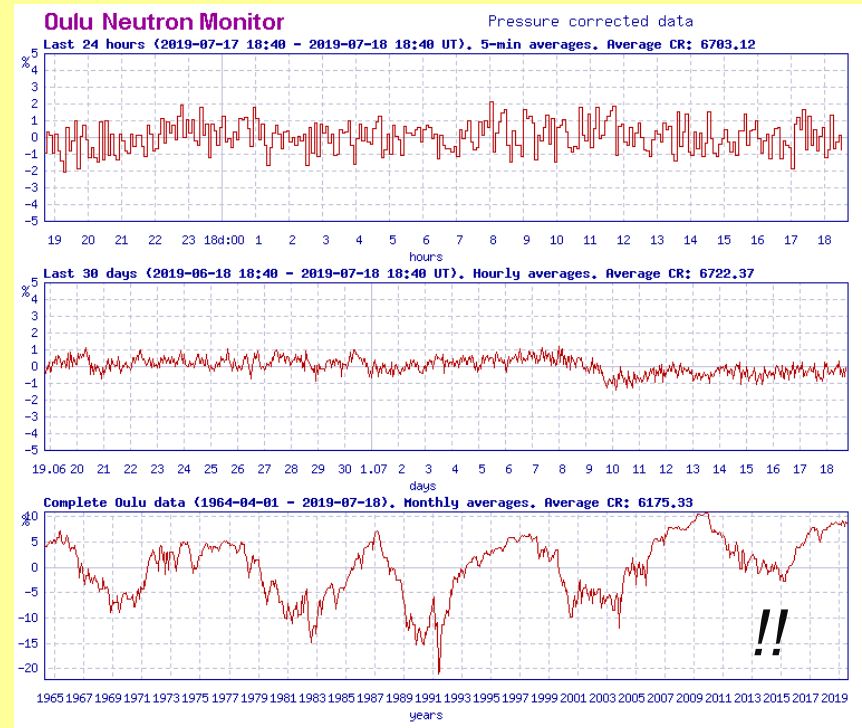- *Spectrum may have steepened (Moraal, Leske, Jokipii)*
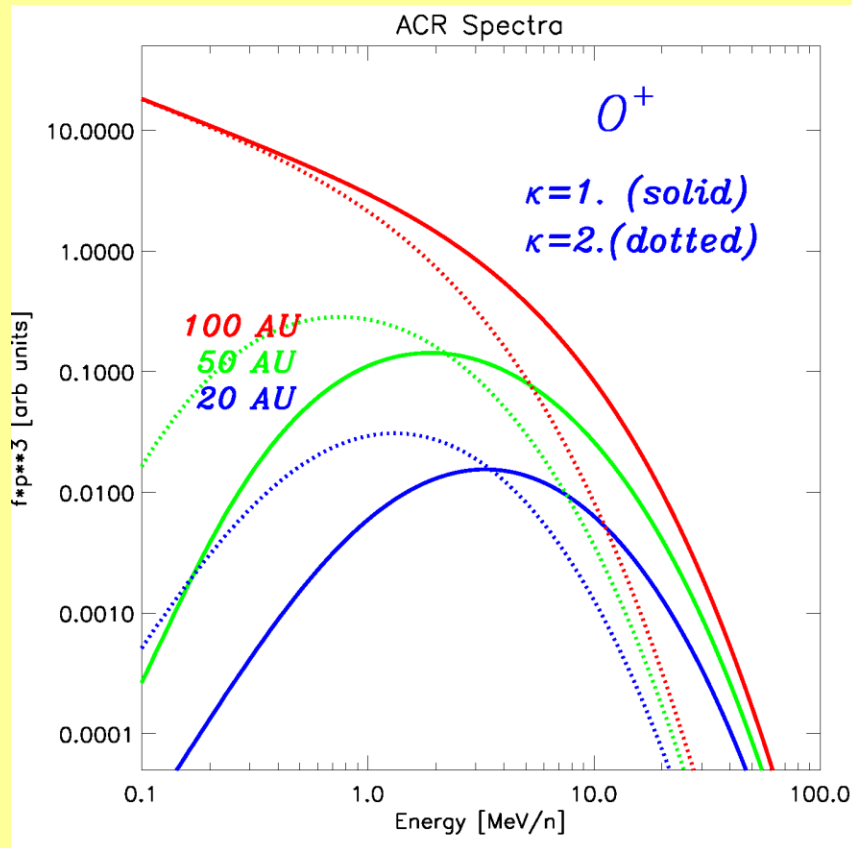
What happens next?
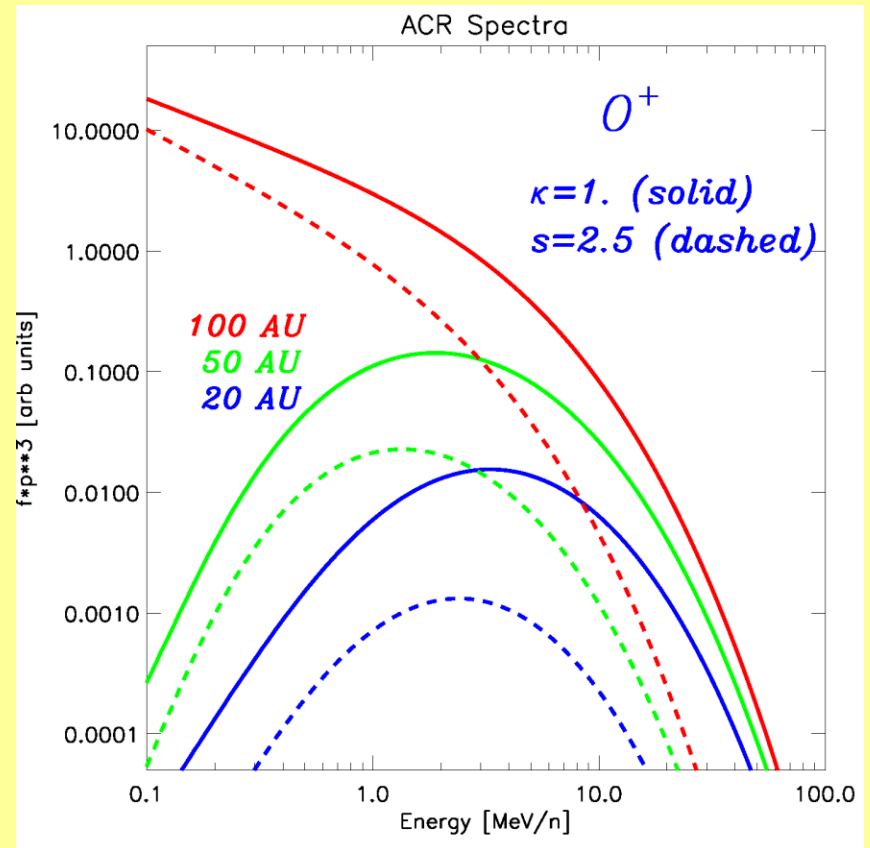
HCS tilt from Stanford
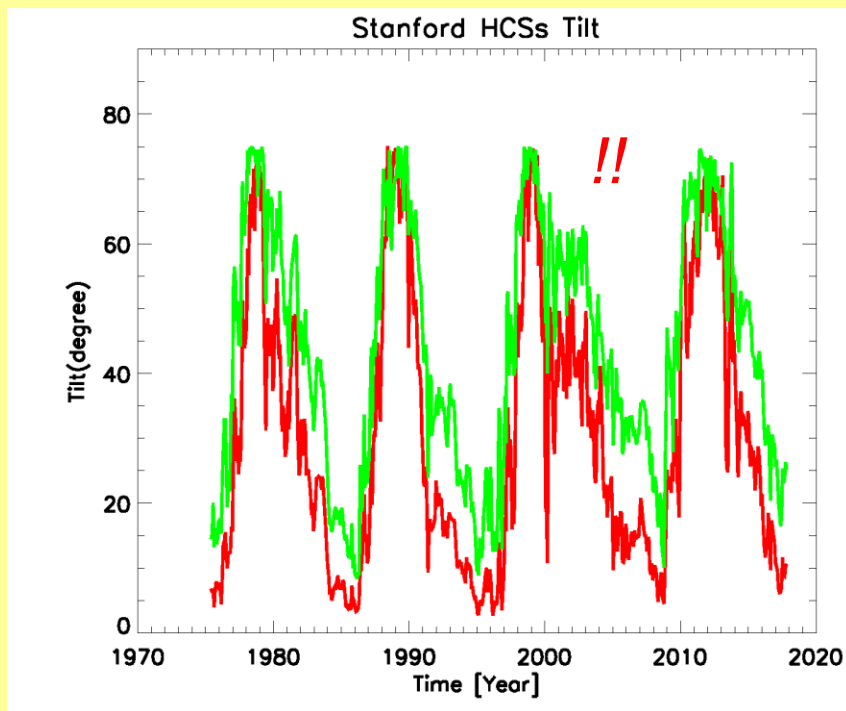
Oulu Neutron Monitor (Usoskin)

Weak modulation in last solar Max
High A>O GCR intensities now
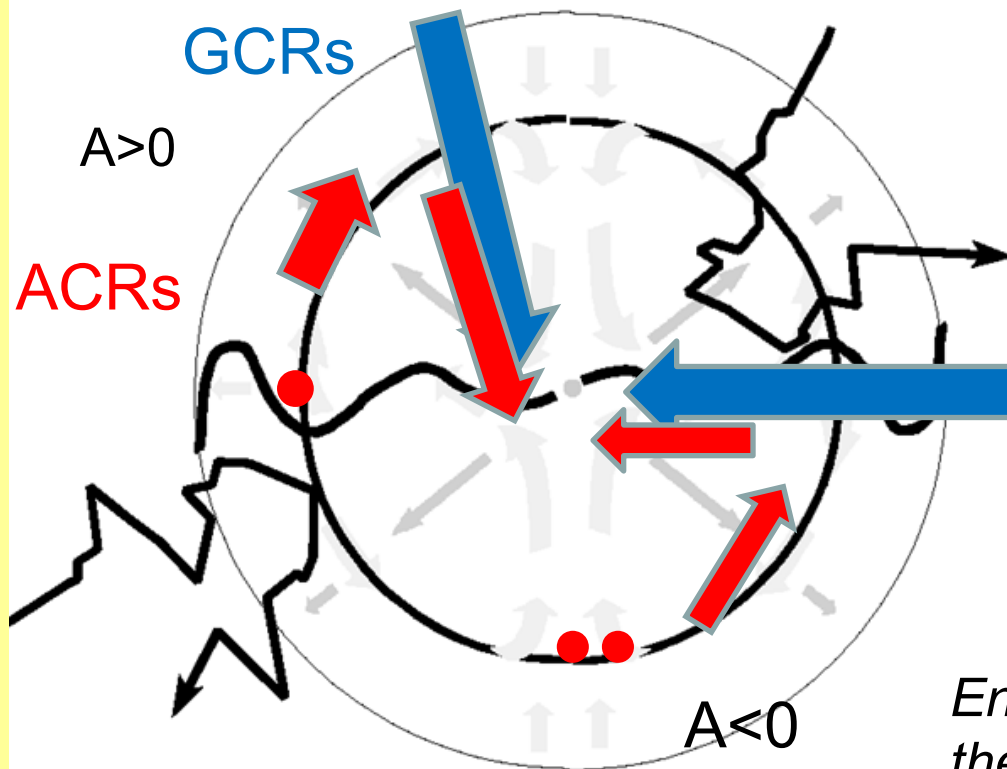
Faster diffusion = softer spectrum
(Moraal 2010)

Doubling the diff.coeffs, κ

Weaker shock (from 3 to 2.5)

ACRs vs *GCRs*: Drift & injection

A. 7-8 Years around Sunsport Minimum

GCRs

A>0

ACRs

A<0
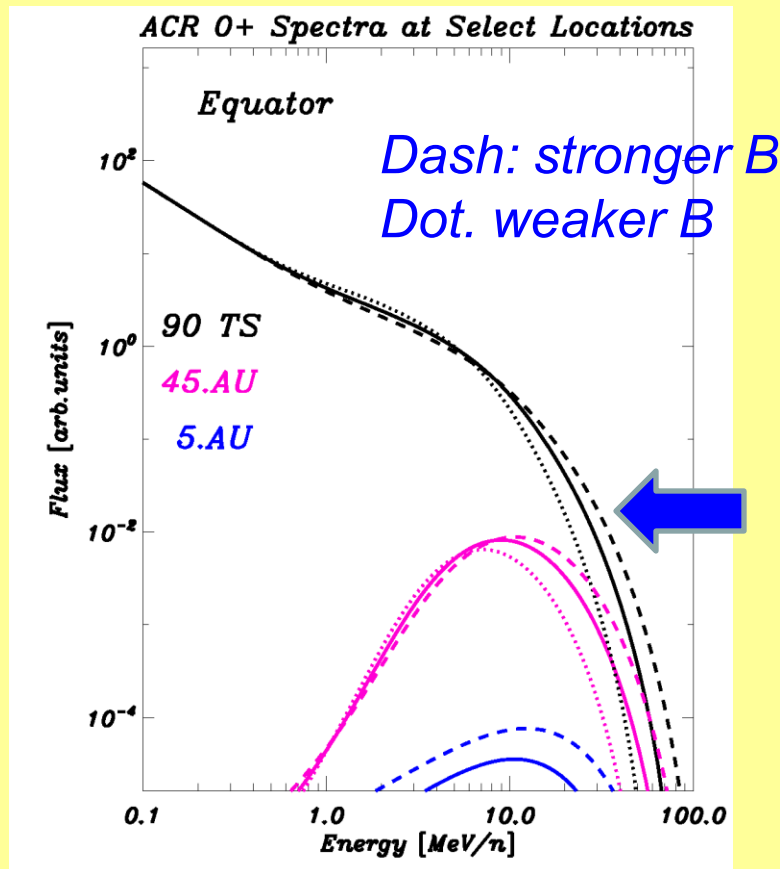
High energy ACRs are injected at:

- *Equator for A>0*
- *Pole For A<0*

Energy gain is limited by the Electrostatic potential (Jokipii, 1996)

ACRs drift along the shock when accelerate

# ACR O+ Changing B only (κ unchanged)

ACR O+ Spectra at Select Locations

Equator

Dash: stronger B
Dot. weaker B

90 TS
45.AU
5.AU

Flux [arb.units]

Energy [MeV/n]

- *Φ i.e potential of the VxB electric field between the Pole and equator is decided by the total iopen magnetic flux (independent of V)*

- *The rollover energy of ACRs is decided by the ACR charge times Φ*

- *Weaker field results in lower rollover energy and lower ACR flux at earth*

A<0: weaker B cutoff shifts to lower energy, not for A>0

'Hoop' model of Parker Spiral Field
Solve Parker's equation in 2-D + energy
### *using ad-hoc parameters*
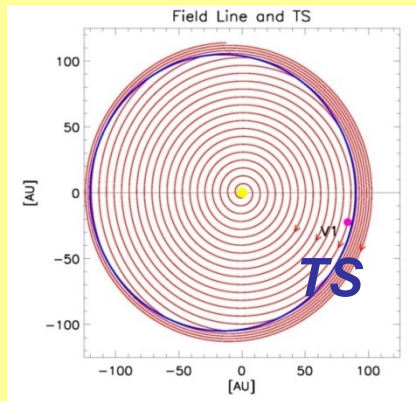
26-day rotation + *radial solar wind* = *tightly wound spiral field*

*CR transport beyond 10 AU is mostly across the spiral
Substitute spiral with hoops: azimuthal symmetry
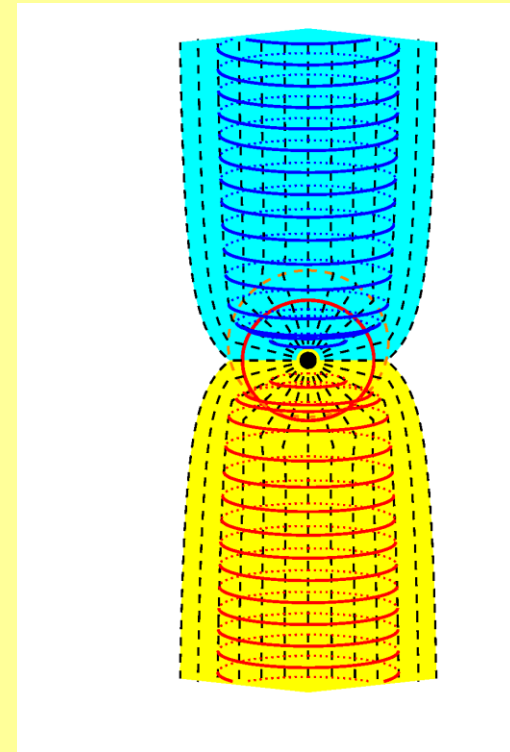The waviness of HCS results in **time-variations***

Drifts in the Heliosheath:
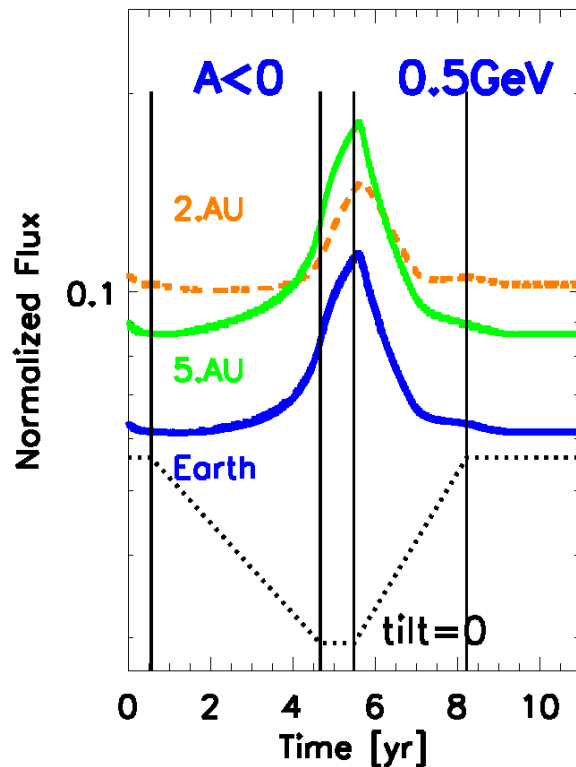## two models of heliotail

Conventional model
elongated tail

Croissant (Opher & Drake)
toymodel (Drake et al, 2015)
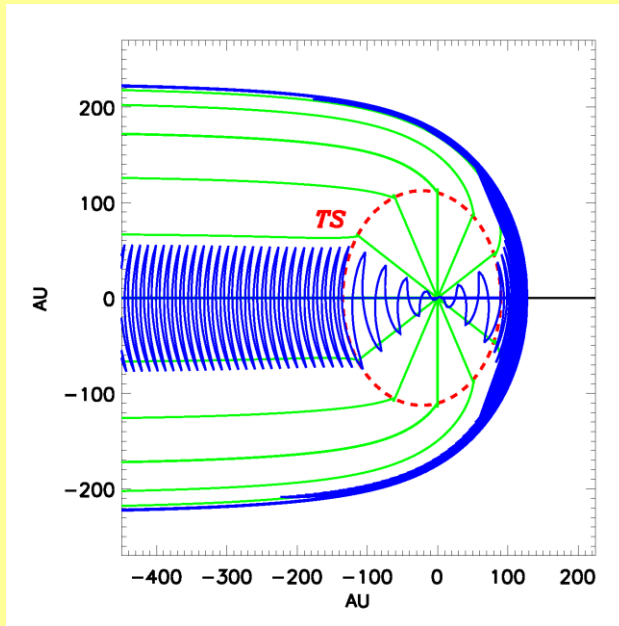
Field lines are stretched & sectors
are compressed New mode of GCR
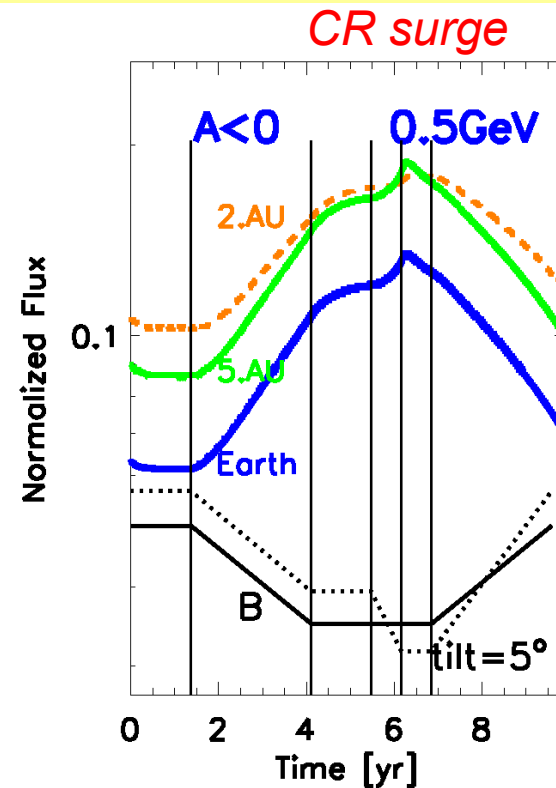transport (Florinski)

Less distorted field structure
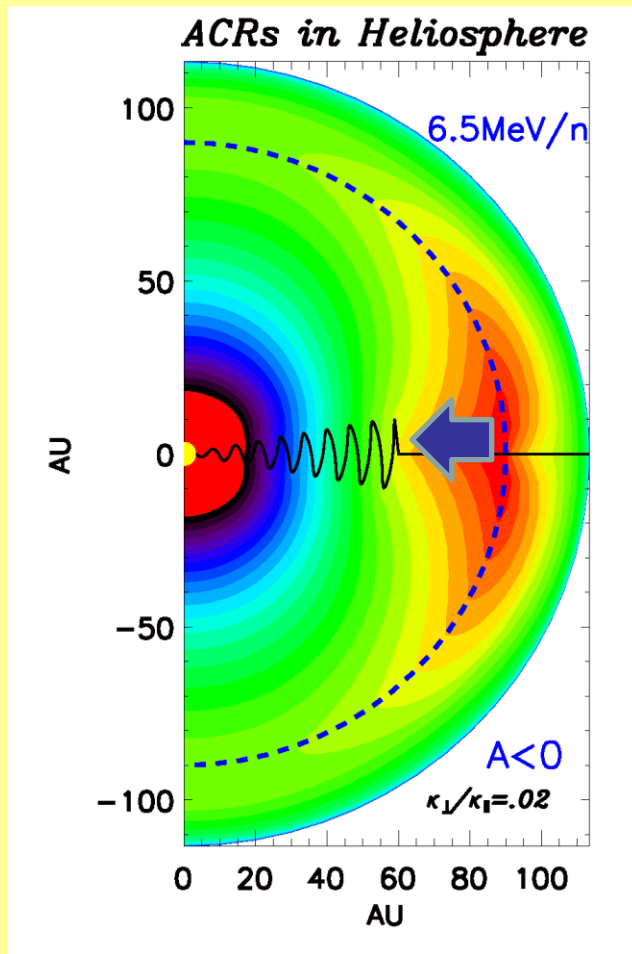
Simulations: Modulation of GCRs

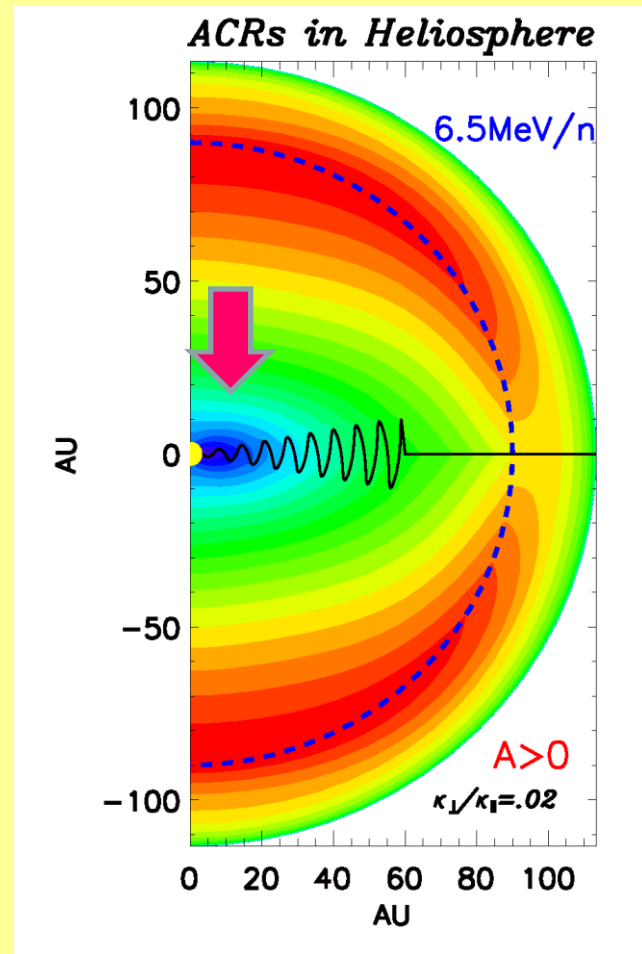*Changing tilt only (70-0-70): GCRs insensitive to high tilt , Peaks when HCS flattens*

Changing B and tilt : Qualitative similarity with observations
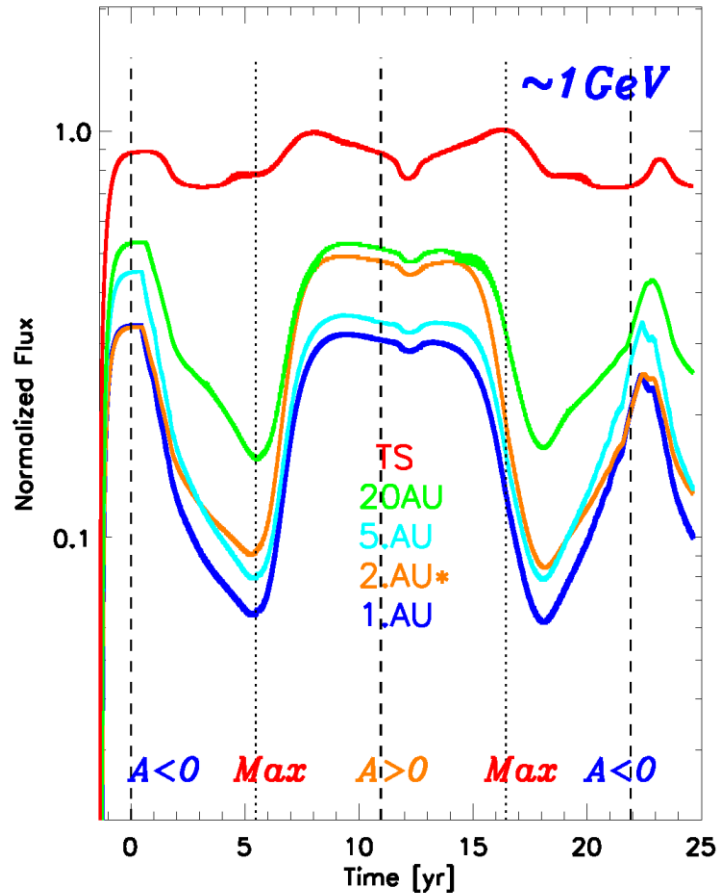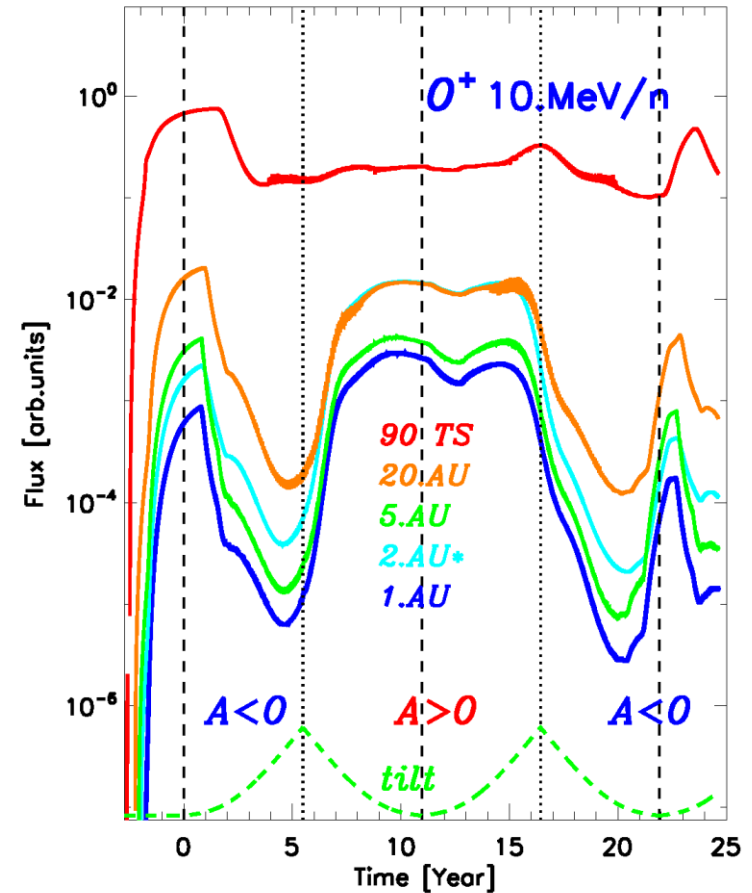
ACRs: Simulation with 10 degree tilt

A<0   A>0

Changing the tilt angle only

GCRs

ACR O+

!! Bump appears only if HCS is flat for a long time

Summary

- *Last unusual solar Minimum offers unique possibilities to gain new insight into the modulation mechanisms*

- *GCRs are in qualitative agreement with expectations and simulations*

- *In addition to other effects, ACR source intensity at TS may be lower because of*
- *(1) Reluctant flattening of HCS*
- *(2) Decrease of total magnetic flux of the Sun, that gives smaller Pole-Equator potential*

- *Work in progress, trying to put pieces togethet*
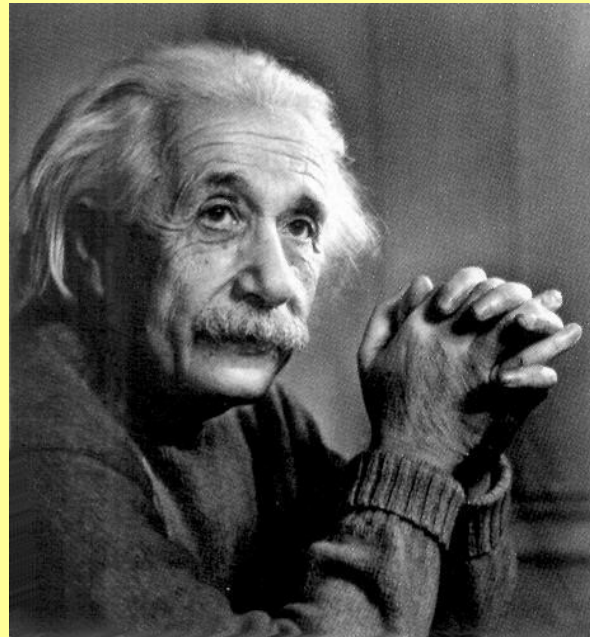
Where do we stand now ?

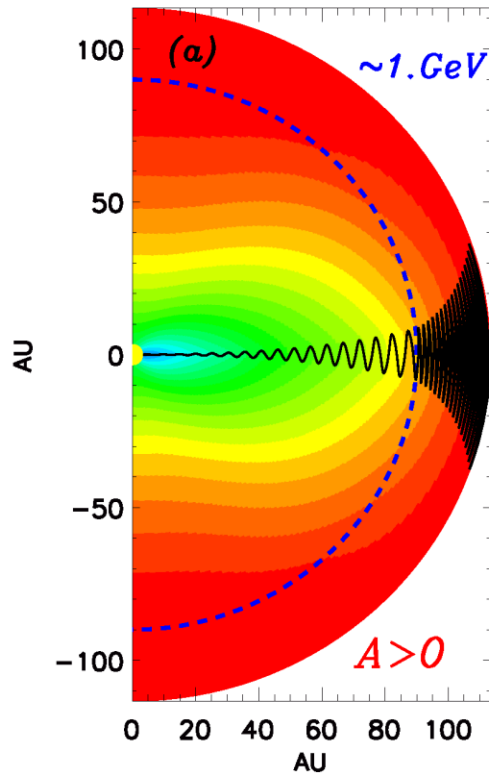Trying to put all pieces in place

Concept/Approach

- "*Make everything as simple as possible, but not simpler* "
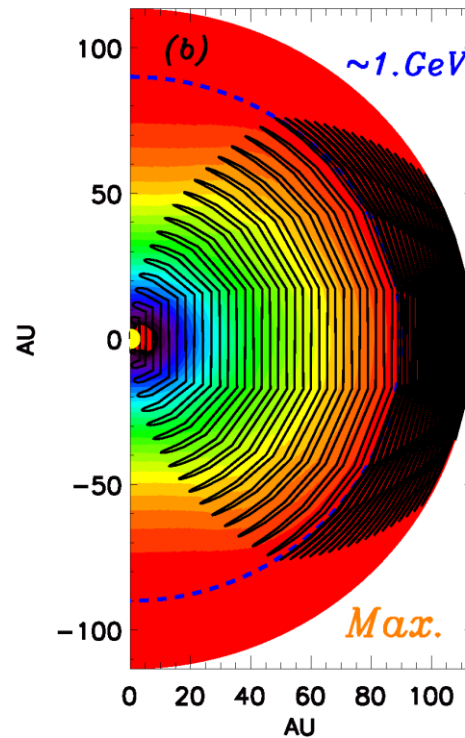
  Make 2D model but Preserve waviness of HCS
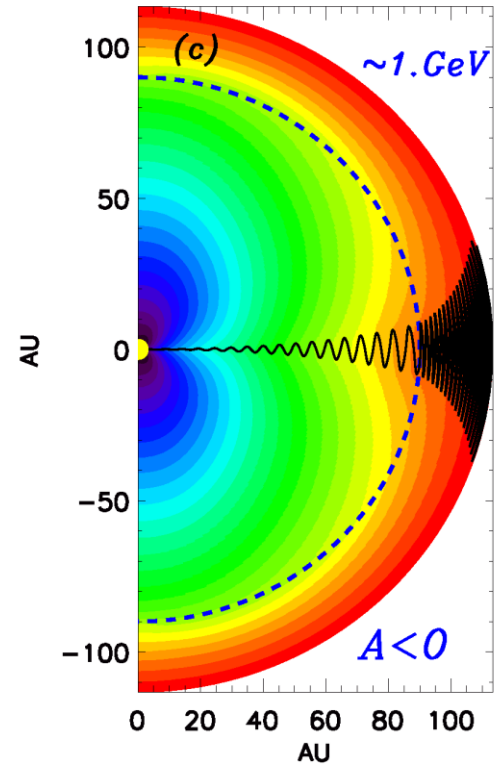
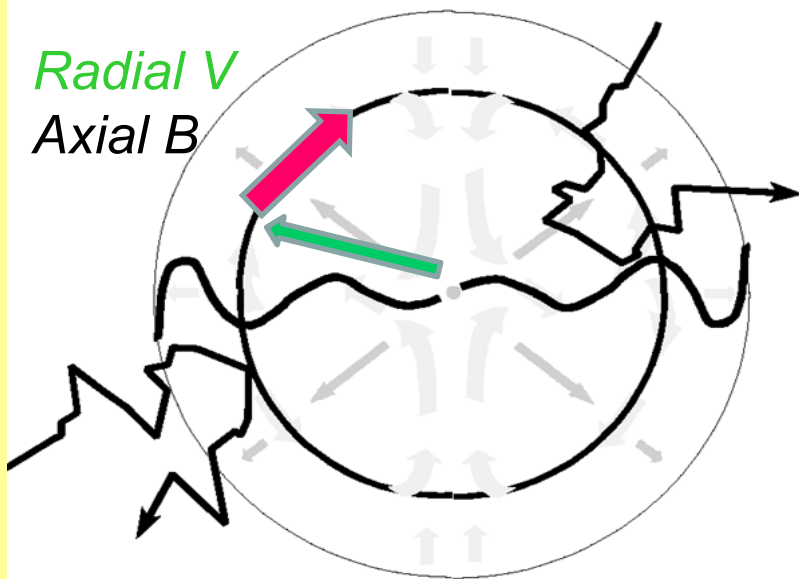# Simulations in a "hoop" model

Solar Min A>0   Solar Max.   Solar Min. A<0

Pole-to-Equator Potential from VxB
is Ω/(2πc)*open magnetic flux

A. 7-8 Years around Sunsport Minimum

Radial V
Axial B

Frozen-in Corotating Magnetic Field, **B**:

$$\mathbf{B} = \frac{B_0(\theta)}{(n_0 V_0)} n (\mathbf{V} - \Omega \times \mathbf{r})$$

Electric field, $\mathbf{B} \times \mathbf{V}$:

$$\mathbf{B} \times \mathbf{V} = (\Omega \times \mathbf{r}) \times \mathbf{B}$$

Pole-to-Equator Electrostatic Potential, Φ
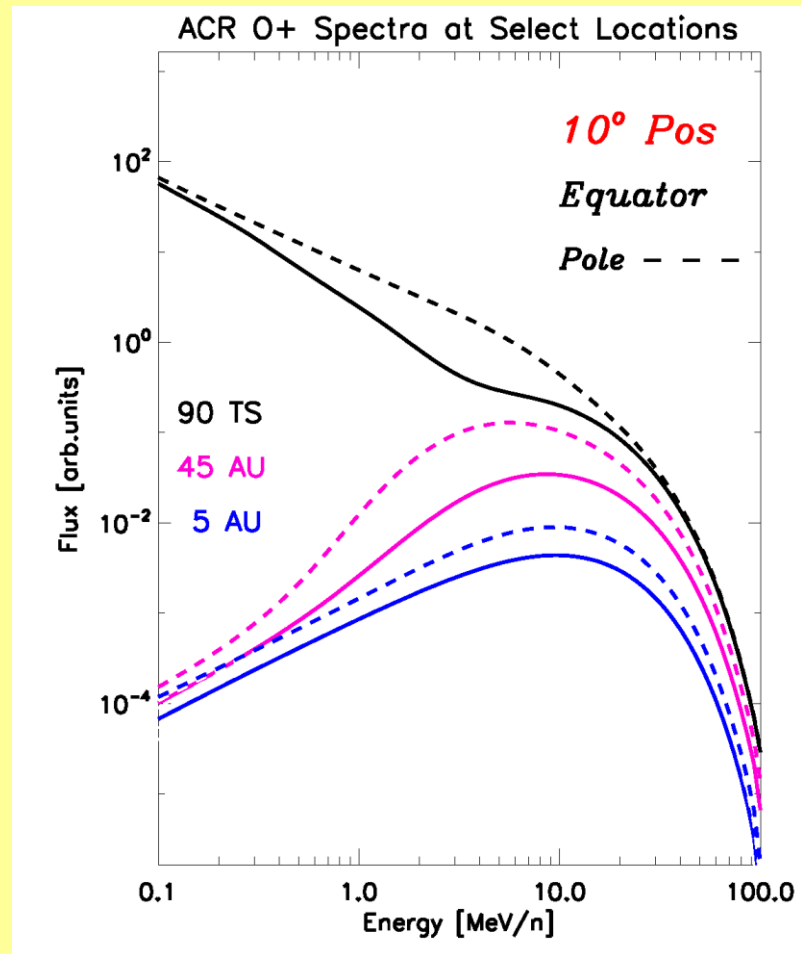
$$\Phi = \frac{\Omega}{2pic} \int_0^{\pi/2} \mathbf{B} d\mathbf{S}$$

is given by the **total hemispherical magnetic flux**

*Φ=Ω/(2πC)*magnetic flux* in one hemisphere*

ACRs 10 degree tilt

ACR O+ Spectra at Select Locations

10° Neg

Equator

Pole - - -

90 TS

45 AU

5 AU

A<0

ACR O+ Spectra at Select Locations

10° Pos

Equator
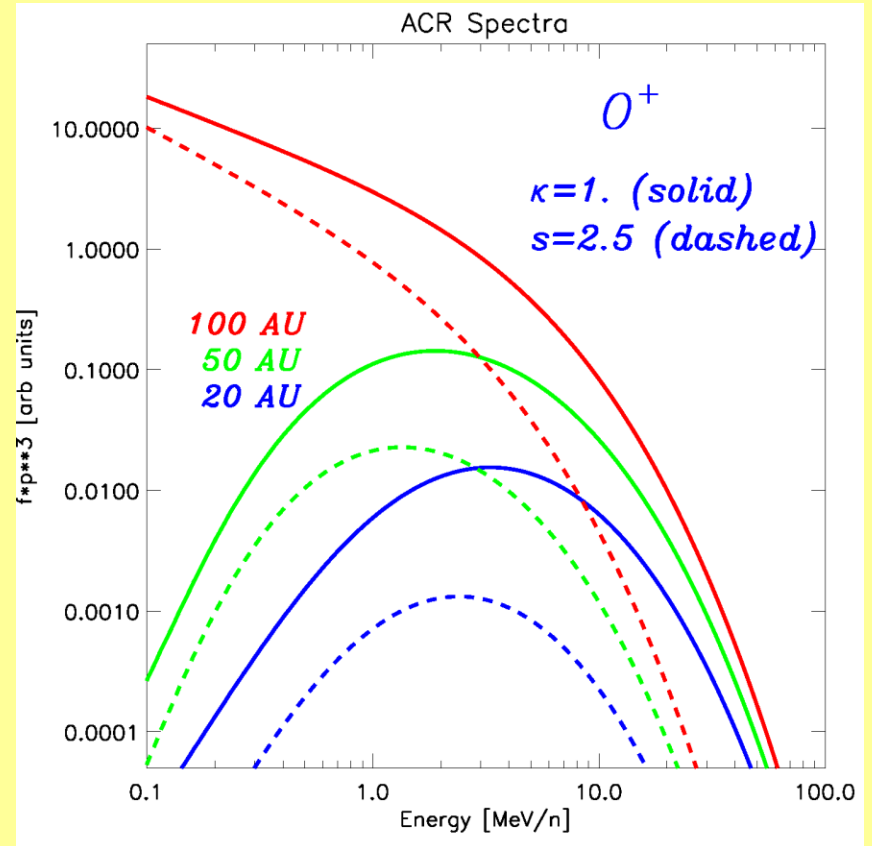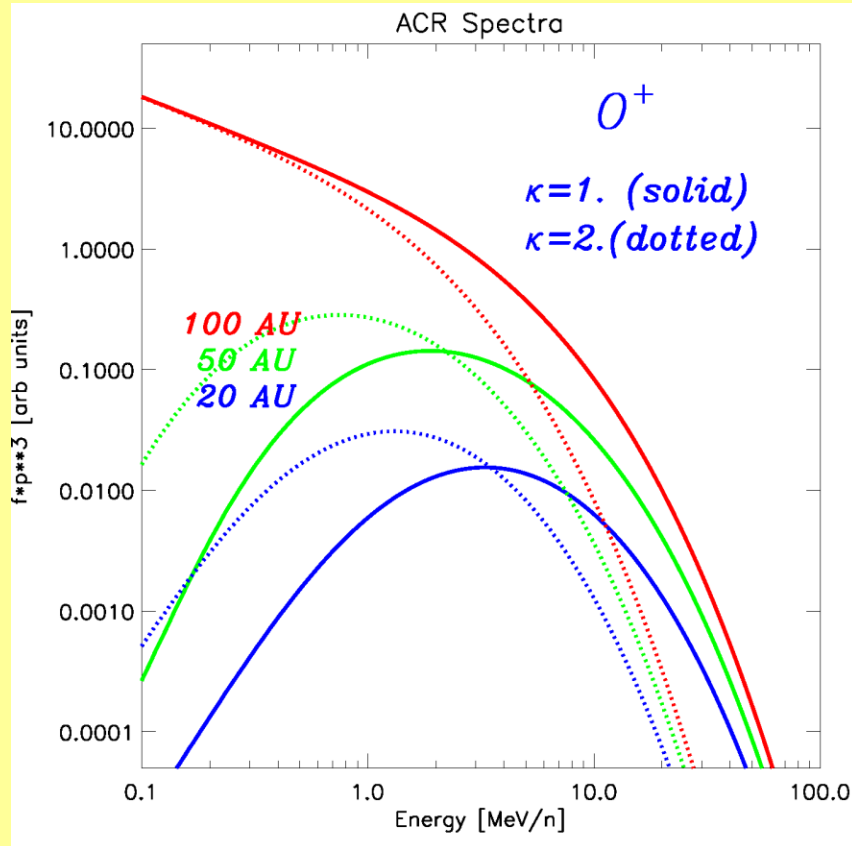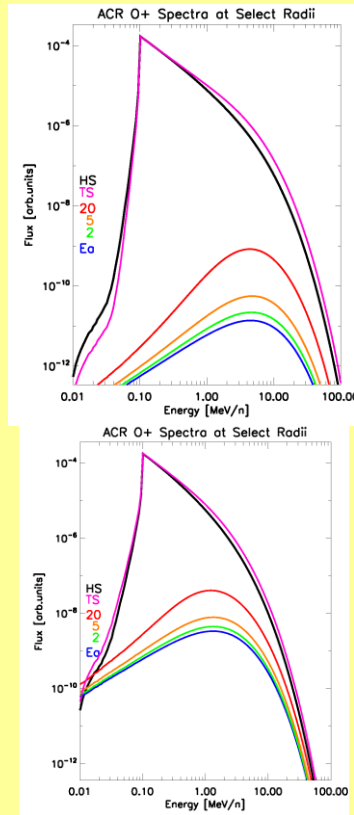
Pole - - -

90 TS

45 AU

5 AU
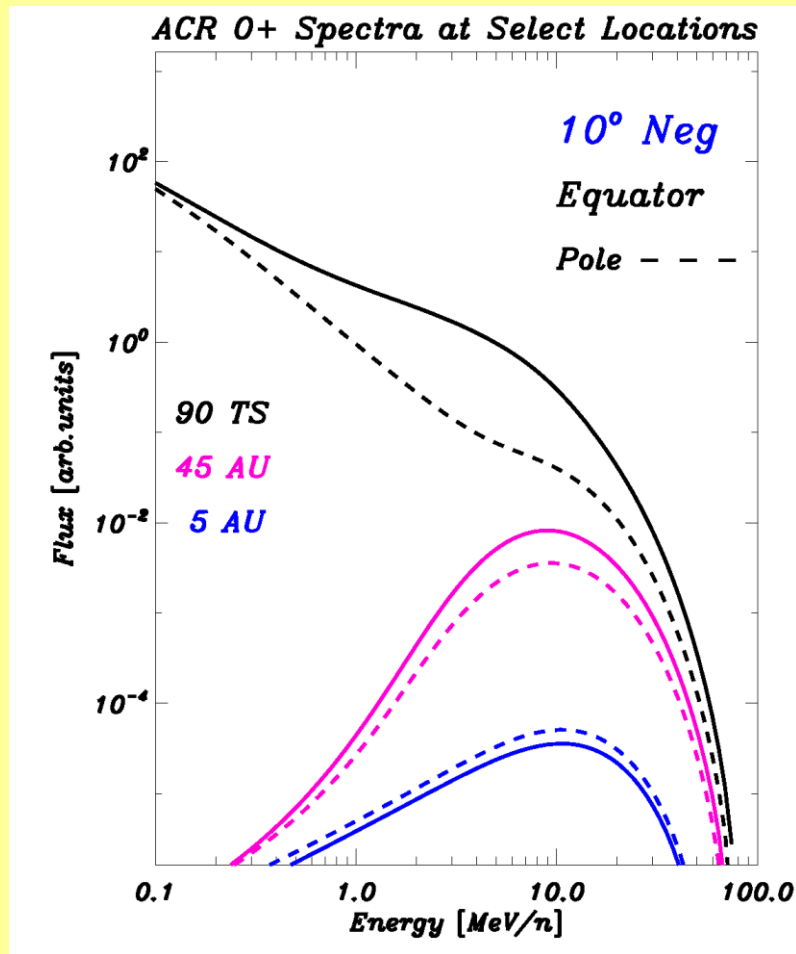
A>0

Spherical model B and S

Steepening ACR Source Spectrum at TS?

Solar Max: Harder

Solar Min: Softer

- *Plane shock*

- *Spherical (cooling):*

$$\gamma = -\frac{3V_1}{\Delta V}\left(1 + 2\frac{\kappa_1}{RV_1}\frac{V_2}{V_1}\right)$$

- *Escape:*

$$\gamma = -\frac{3V_1}{\Delta V}\left(1 + 2\frac{V_2}{V_1}\frac{Q}{1-Q}\right)$$

$$Q = exp\left(-\int_{R_s}^{R_2}\frac{V}{\kappa dr}\right)$$