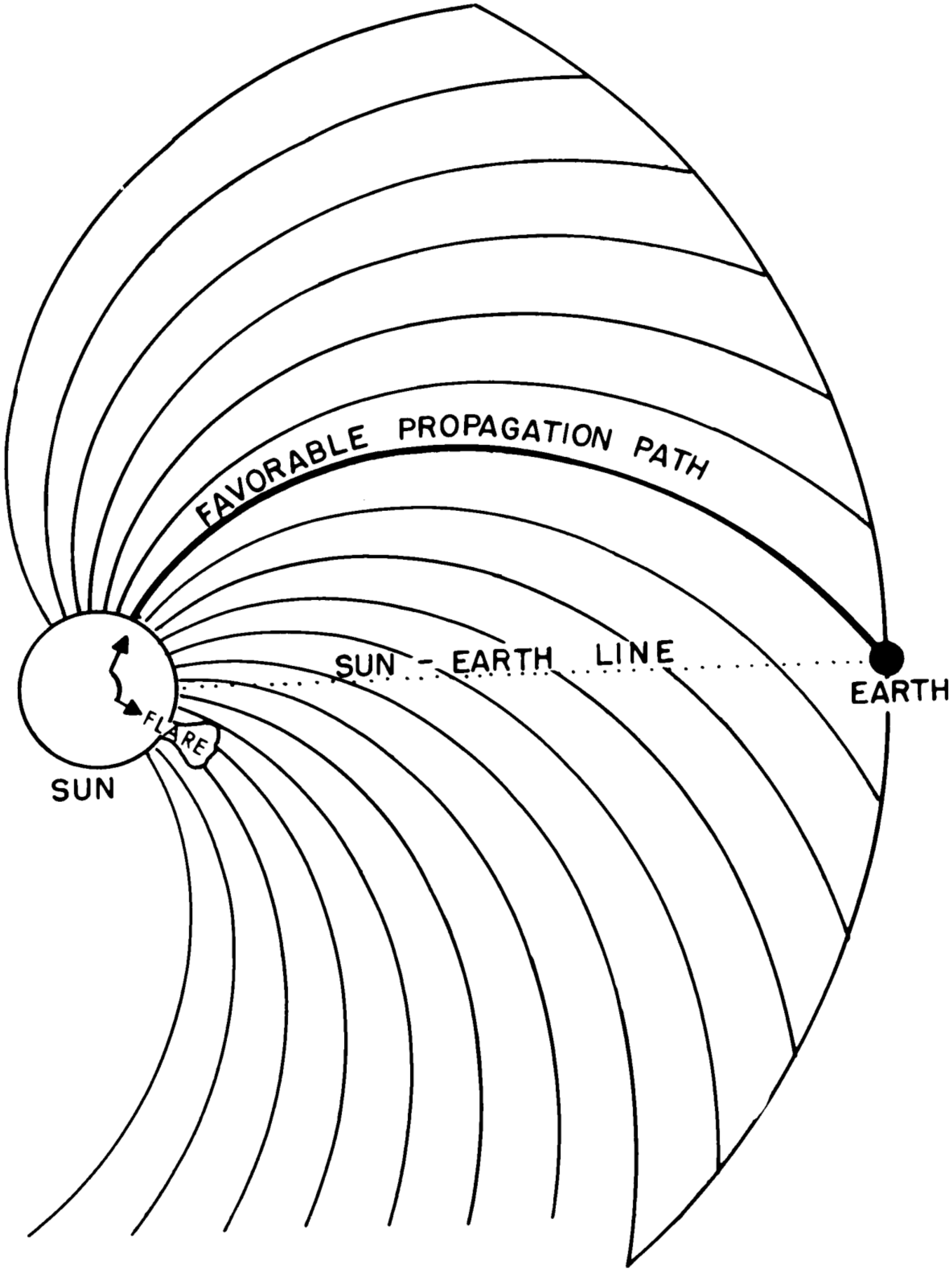
SOLAR COSMIC RAY GROUND-LEVEL EVENT (GLE) ANISOTROPY

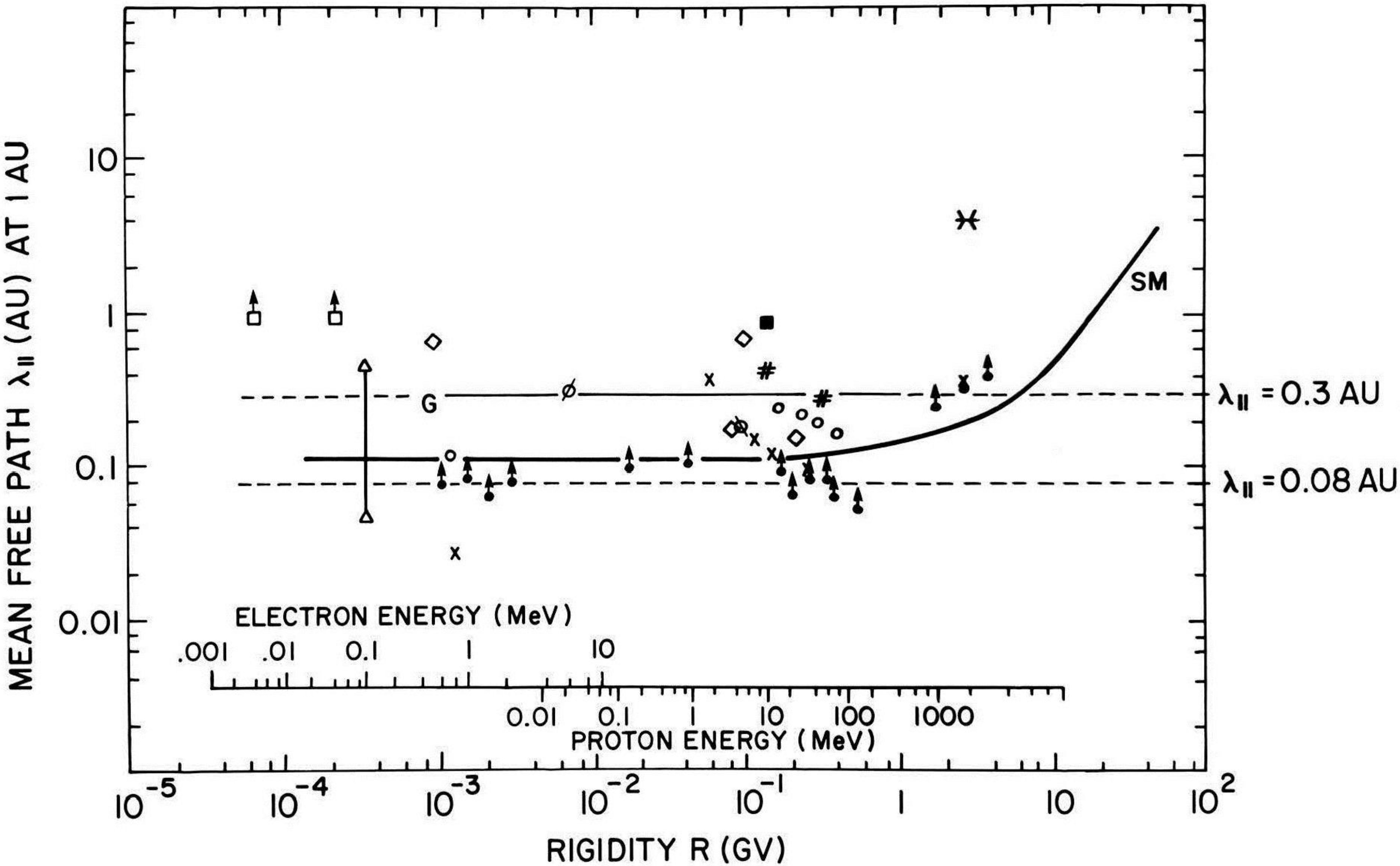
D. F. SMART and M. A. SHEA
AFRL (Retired)
SSSRC, NASHUA, NH, USA



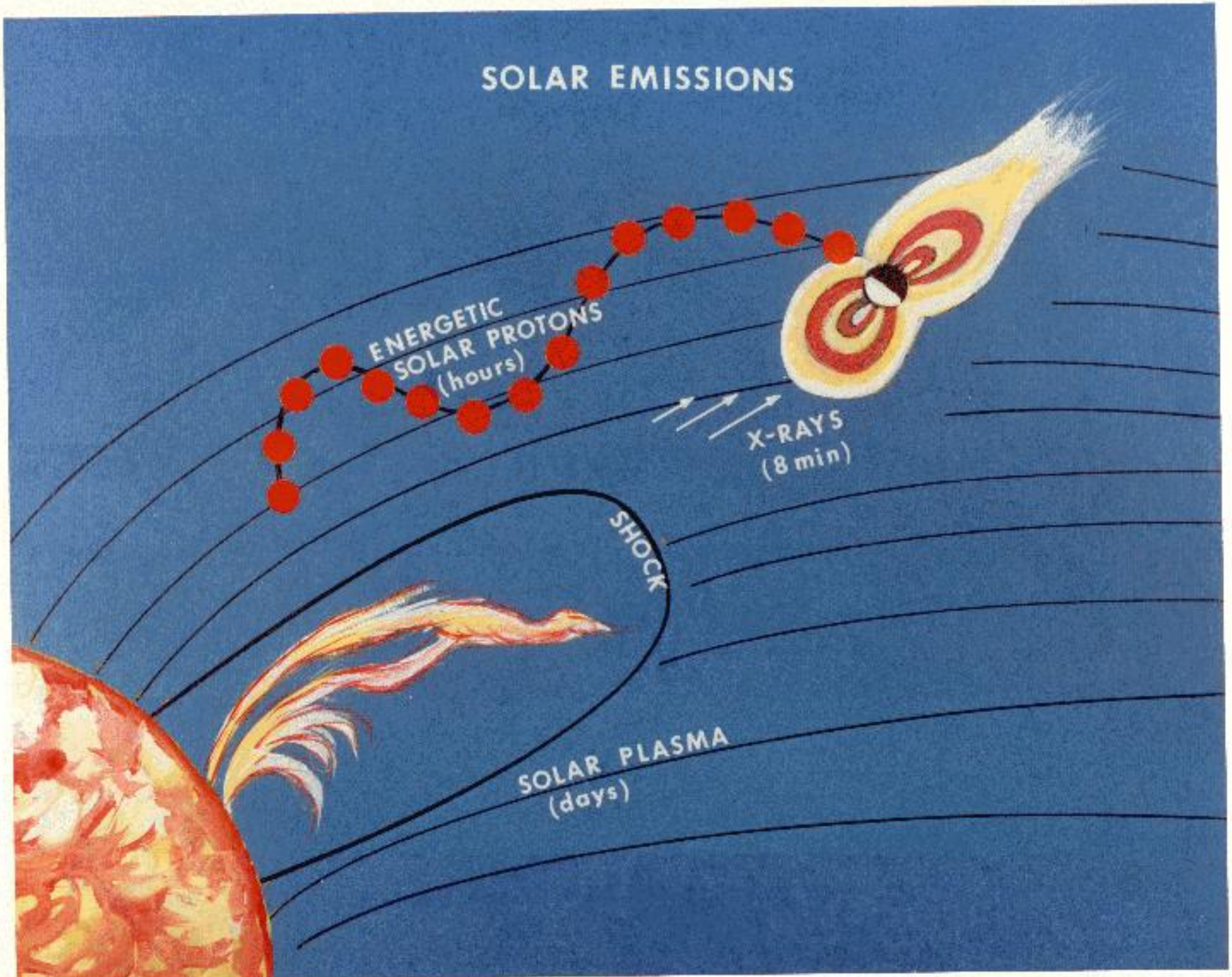
The interplanetary magnetic field controls charged particle propagation between the Sun and the Earth

An idealized concept is the Archimedes spiral curve in the IMF topology.

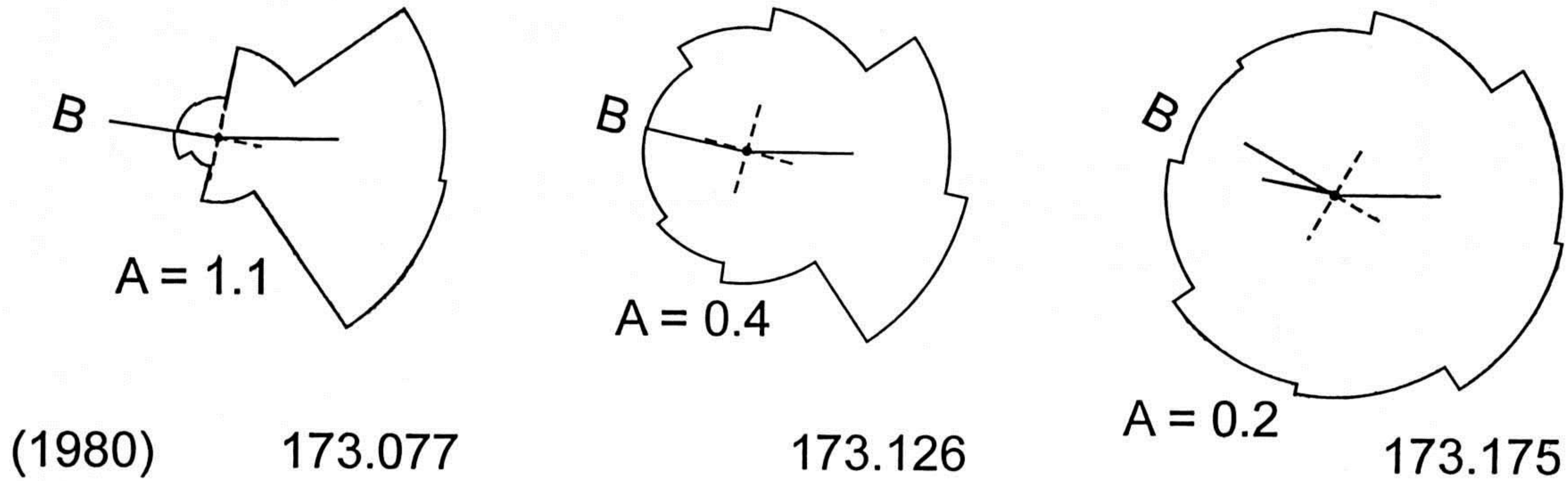
The IMF is actually turbulent, with magnetic scattering centers.



The average mean free path in the IMF is the order of 0.1 AU. With order of magnitude variations.


SOLAR EMISSIONS
ENERGETIC SOLAR PROTONS (hours)
X-RAYS (8 min)
SHOCK
SOLAR PLASMA (days)

The spinning satellite method for anisotropy.



Sectored proton flux anisotropy (A) at ~30 MeV
The distance from the center indicates the
magnitude and direction of the particle flux.
The "B" line indicates the IMF direction
The center line is the Sun-Earth line.

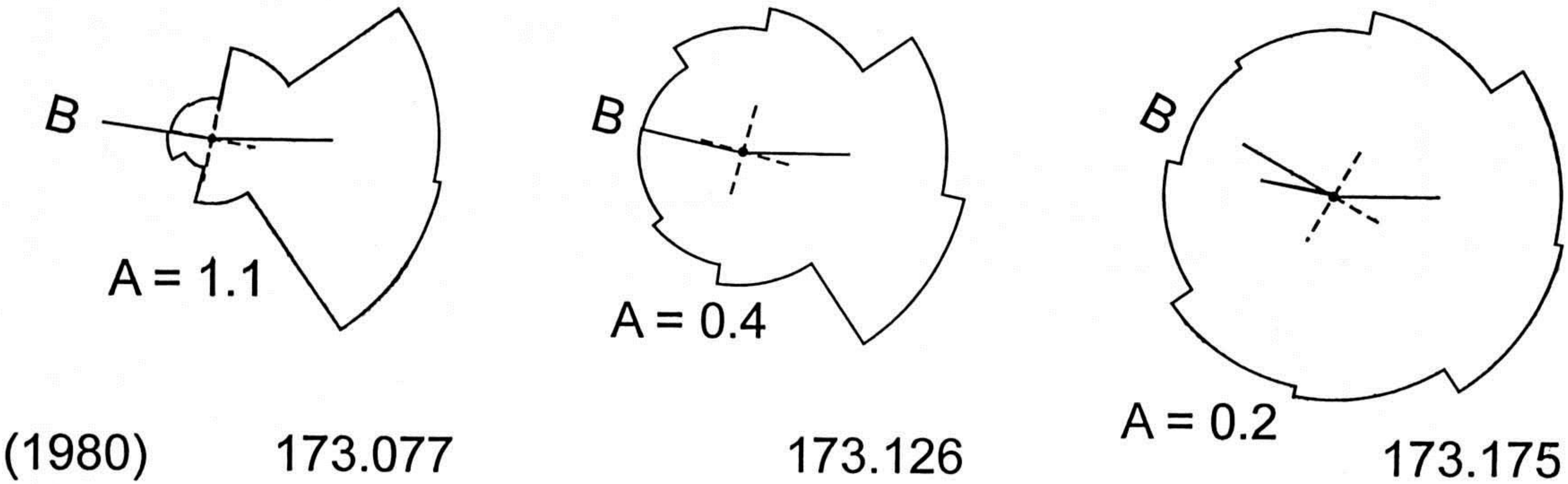
Solar Particle Anisotropy

A directional dependence solar particle flux.

Solar particle anisotropy is radial distance and time dependent

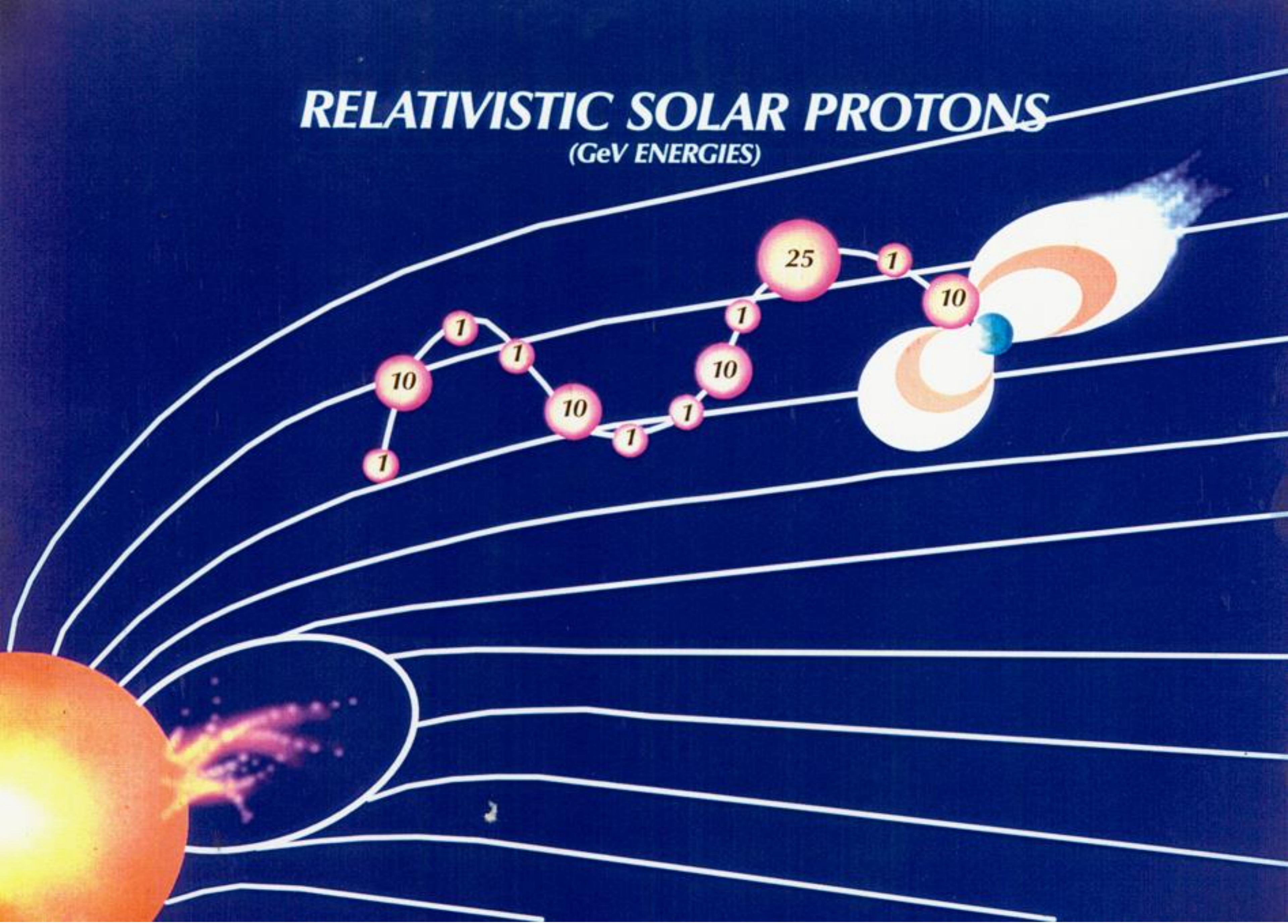
Many definitions	Maximum	Minimum
THEORY	1	0
2 π Forward / 2 π Reverse	Large	1
Forward Sector / Reverse Sector	Large	1
Forward Steradian / 4 π Steradian	Large	1

The spinning satellite method for anisotropy.



Particle flux anisotropy is a transient phenomena; a duration of a few hours is typical.

Multiple sensors on a stabilized satellite can also be used to measure particle anisotropy.

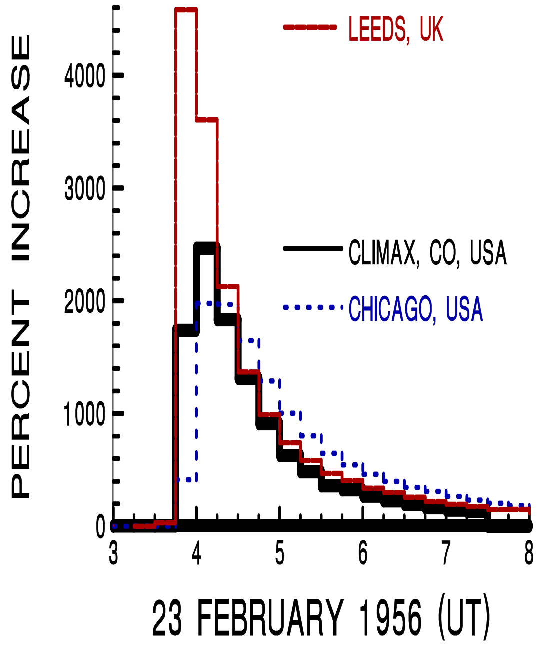

RELATIVISTIC SOLAR PROTONS
(GeV ENERGIES)
1
10
1
1
10
1
1
10
1
25
1
10

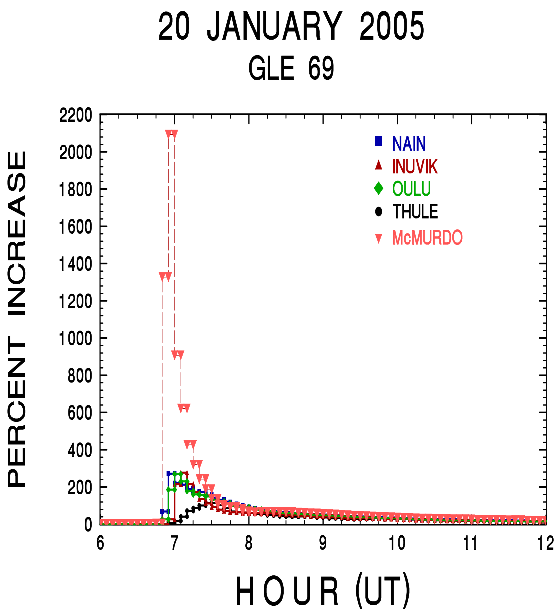
THE LARGEST OBSERVED SOLAR COSMIC RAY EVENTS

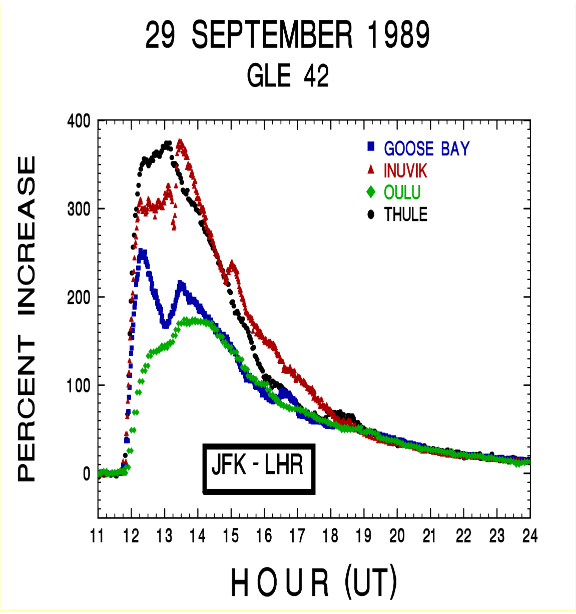
LARGEST GLE
1956 02 23
4580 % (15-min data)
Flare at 23 N, 80W

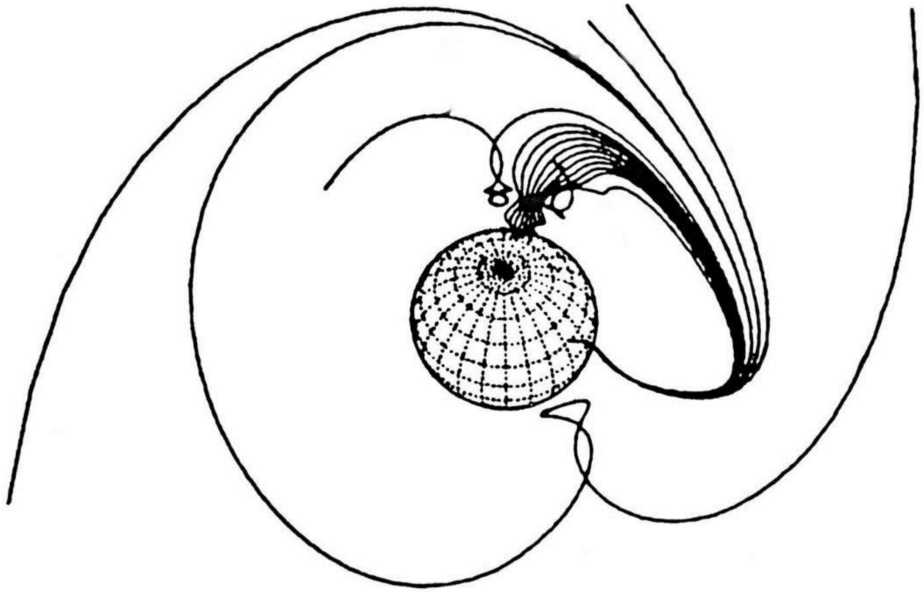
2nd LARGEST GLE
2005 01 20
2150 % (5-min data)
Flare at 14 N, 61 W

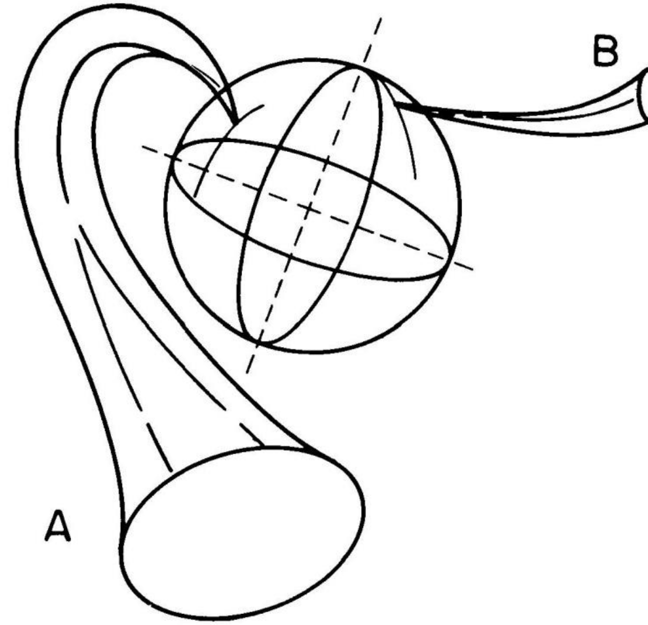
4th LARGEST GLE
1989 09 29
373 % (5-min data)
Flare at 105 W











Cosmic ray trajectories have curved paths in the Earth's magnetic field.

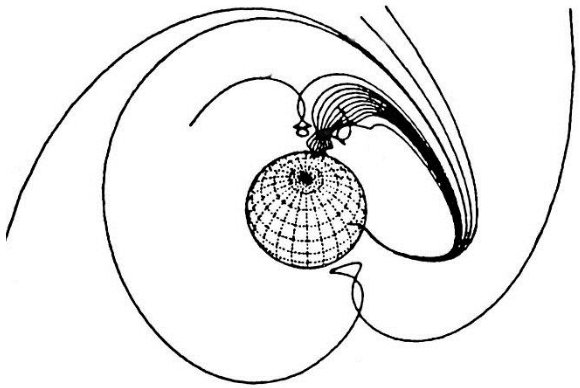
Cosmic ray stations view interplanetary space through allowed trajectories.

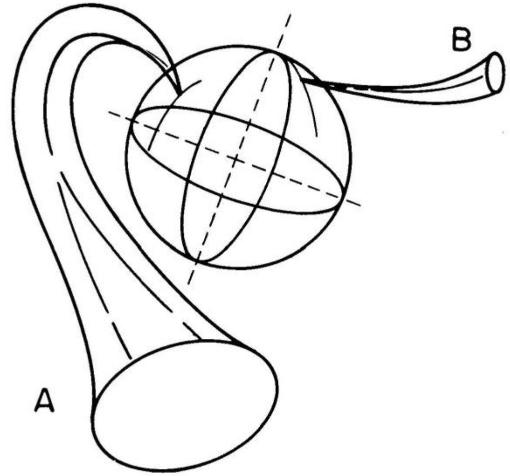
This leads to the concept of the asymptotic cone of acceptance.

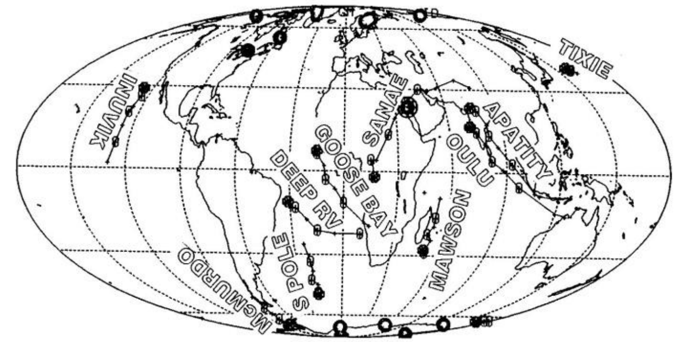
Low and mid latitude stations have wide asymptotic cones of acceptance.

Polar stations have narrow asymptotic cones of acceptance.

As a result, polar stations view a narrow region of interplanetary space.







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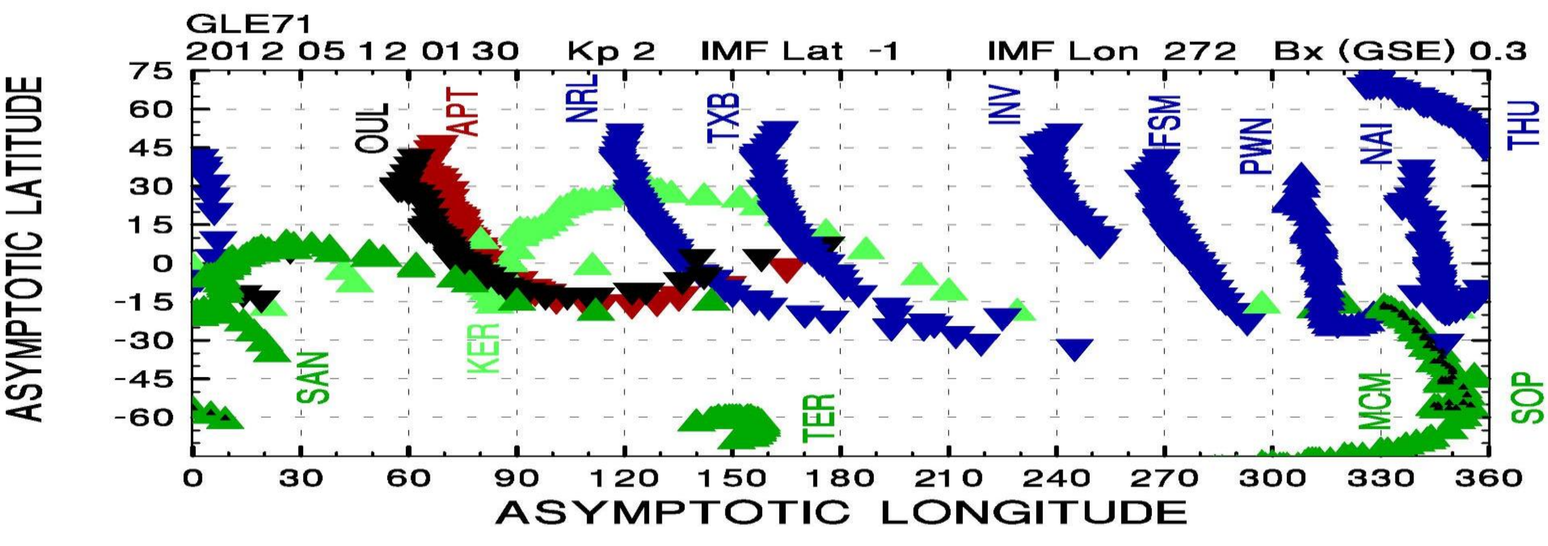
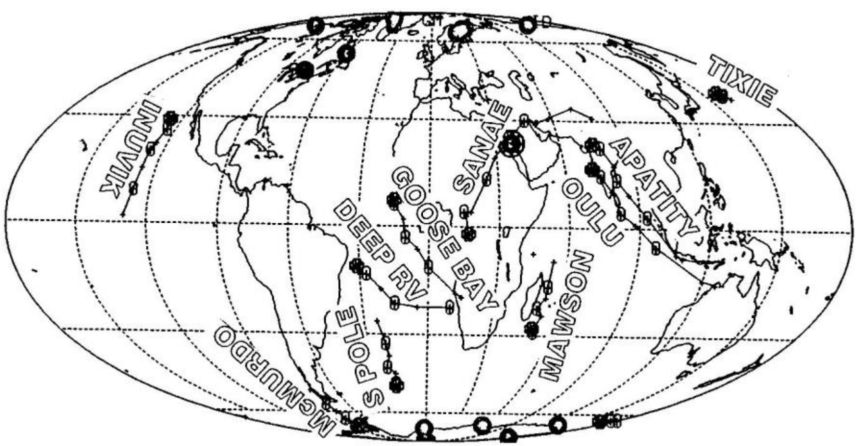


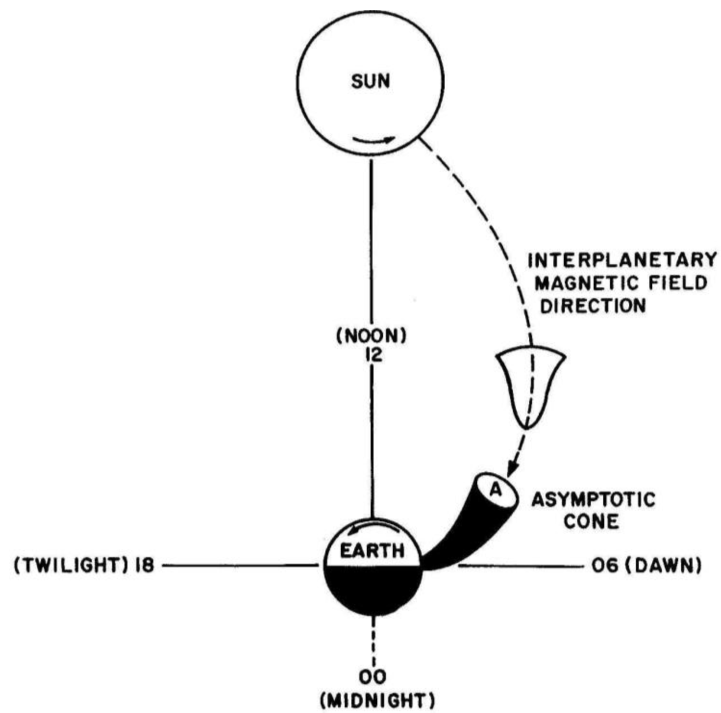
Asymptotic Viewing Cones

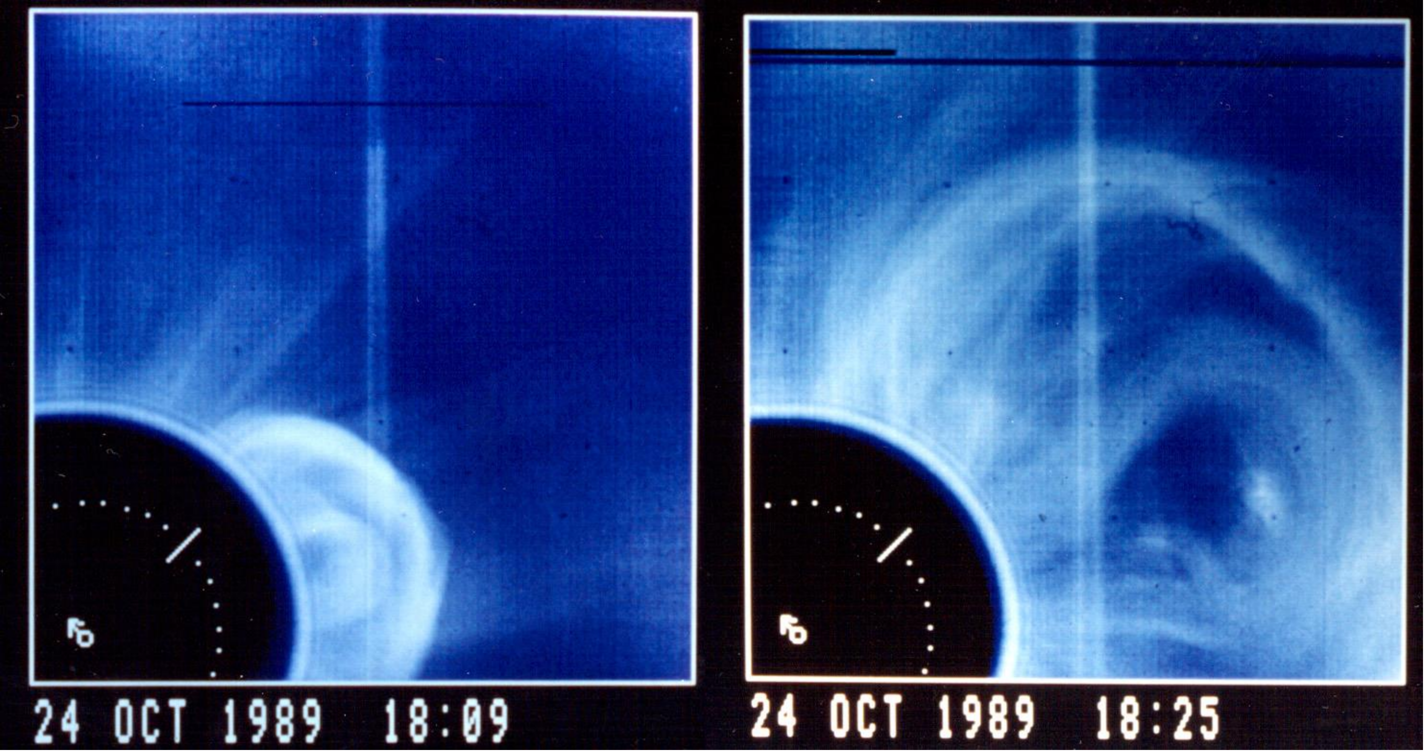
The Earth's magnetic field focuses charged particle trajectories arriving at a cosmic ray station into an Asymptotic Cone of Acceptance.
The higher the particle energy the less magnetic bending of the trajectory .
In the Polar Regions these **Asymptotic Viewing Cones** can be quite narrow.
They become progressively wider at mid and equatorial latitudes.



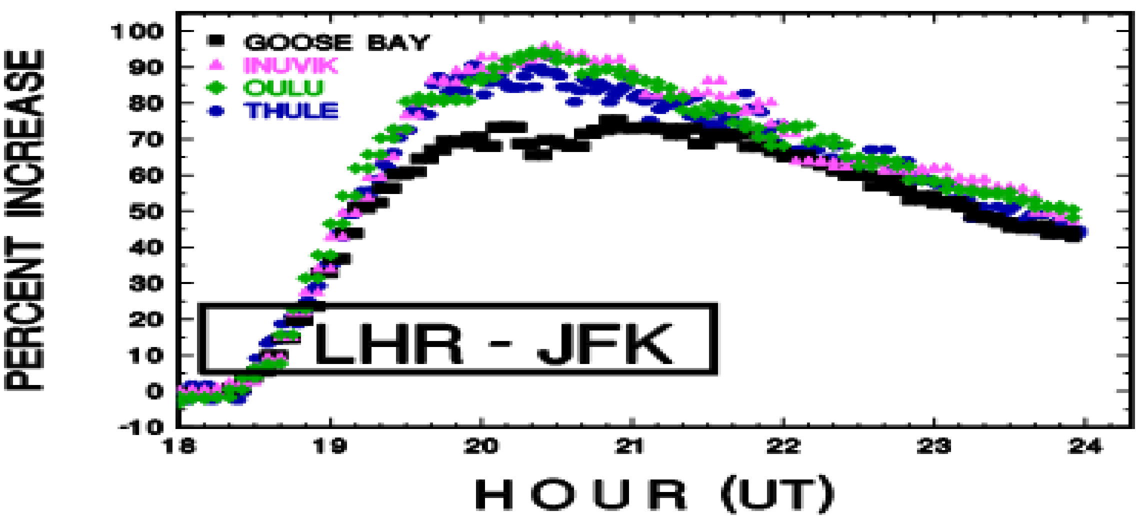
Solar cosmic ray anisotropy

The relativistic solar cosmic rays propagate along the interplanetary magnetic field.
The GLE's associated with activity on the western hemisphere of the sun are usually very **anisotropic** during the initial phase (onset to maximum).
One order of magnitude decrease in particle flux per radian is not an unusual flux gradient.

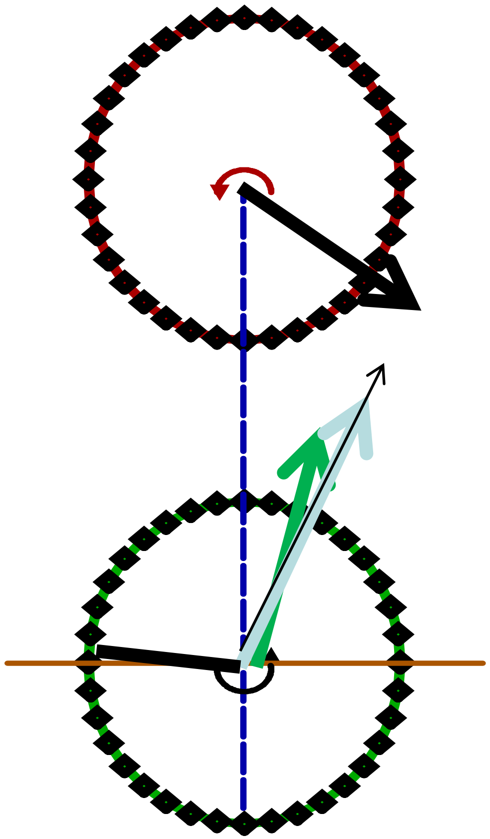


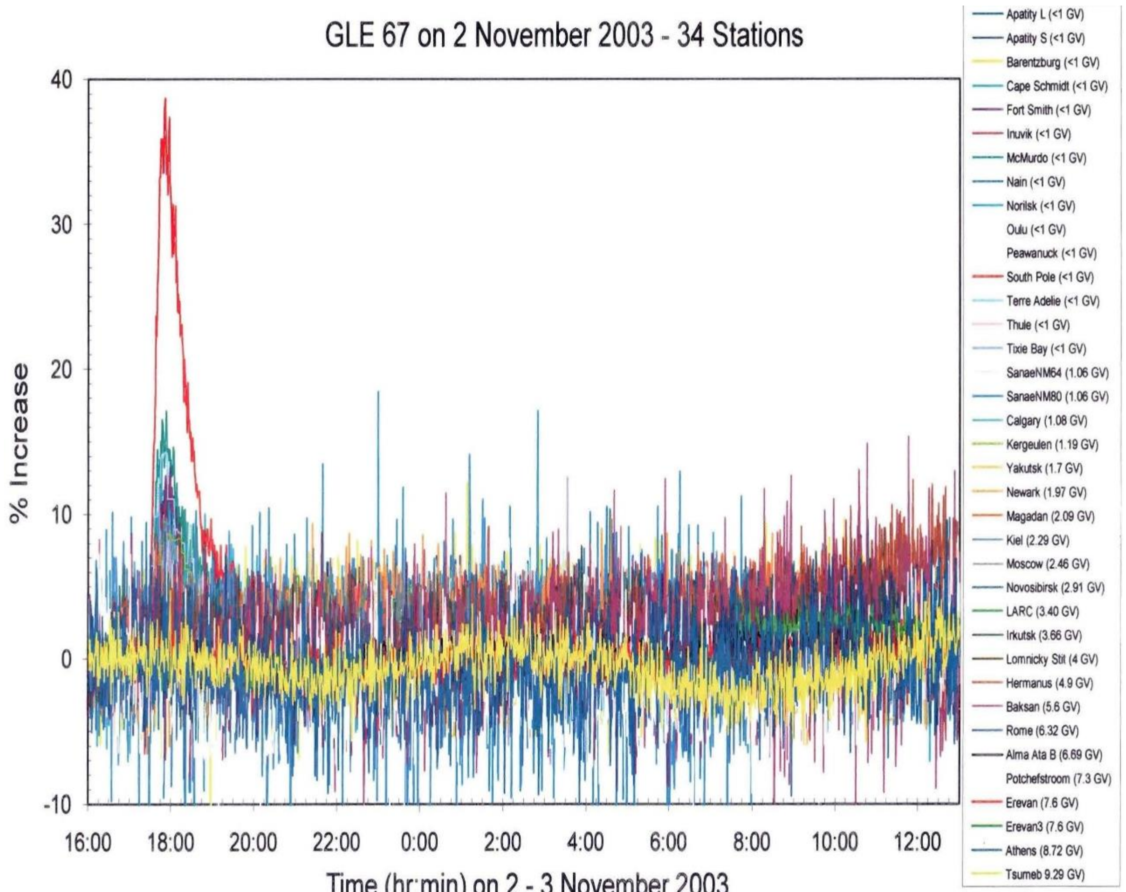


24 OCTOBER 1989
GLE 45



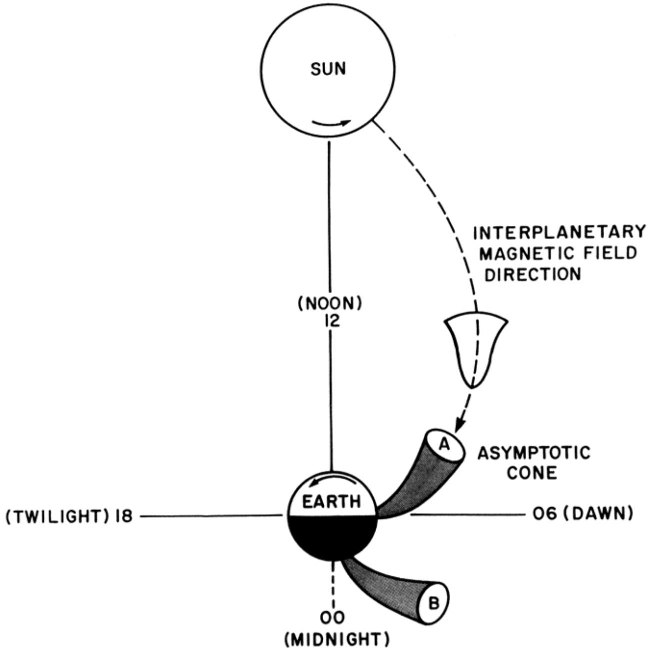
GLE	67	GLE Start	2003 11 02 17 30
Flare	56	GLE Max	2003 11 02 17 35
Bx +1.7, By +0.9, Bz -5.0		Ft. Smith @	12%
IMF	Lat -69, Lon 333	Ft. Smith 2 GV Asy Lon	266
P View	Lat +68, Lon -28	Greenwich Meridian@	84

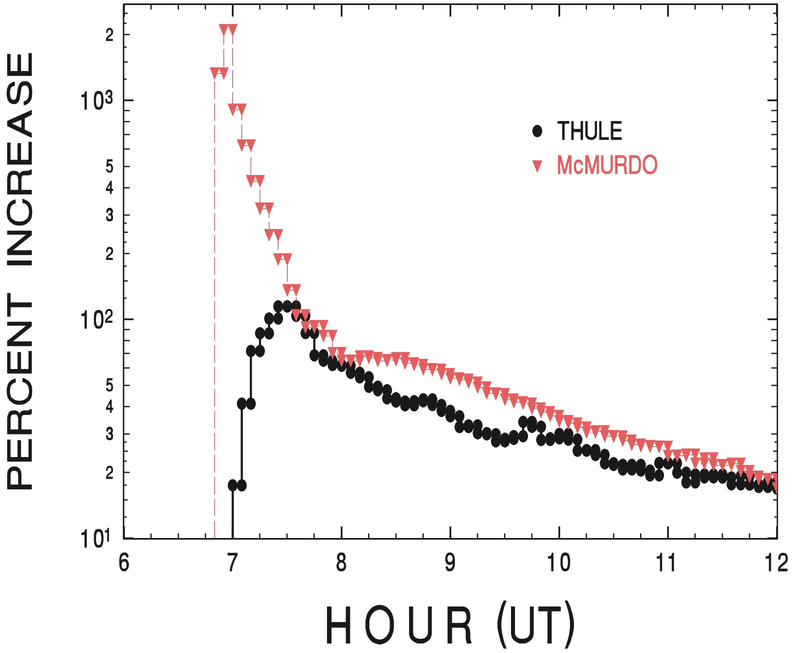




CONCEPT

The ASYMPTOTIC CONE and ANISOTROPIC PROTON FLUX





2005 01 20

GLE 69

The objective is to determine:

(1) The solar particle source direction.
(2) The particle flux anisotropy in space,
(3) The spectral characteristics of solar cosmic rays.

Analysis should reproduce the response of any neutron monitor in the world.

The response of a neutron monitor is given by the following equation.

$$I = \sum_{Pc}^{\infty} J_{\alpha}(\alpha,P)\ S(P)\ G(\alpha)\ ?\ P. \qquad (1)$$

I is the observed increase,
P_c is the cutoff rigidity,
$J_{\alpha}(\alpha,P)$ is the differential flux
*(in the interplanetary medium at pitch angle, α, and rigidity, **P**, through the asymptotic cone of acceptance),*
S(P) is the neutron monitor specific yield (as a function of rigidity),
$G(\alpha)$ is the anisotropic pitch angle distribution.

The initial step is to “calibrate” the neutron monitors

The primary cosmic ray spectrum at the time of the event
transmitted through the asymptotic cone of acceptance
into the neutron monitor yield function gives the **pre-event background**.

The anisotropic solar proton spectrum
transmitted though the asymptotic cone of acceptance into
the neutron monitor yield function determines the **additional increase**

The increase at each neutron monitor is the ratio of

$$\frac{\text{The response from the anisotropic solar particle flux}}{\text{The modulated cosmic ray induced background}}$$

The resulting solar particle flux is in absolute units

protons $(cm^{2}\text{-s-ster-GV})^{-1}$

allowing a direct comparison with space measurements.

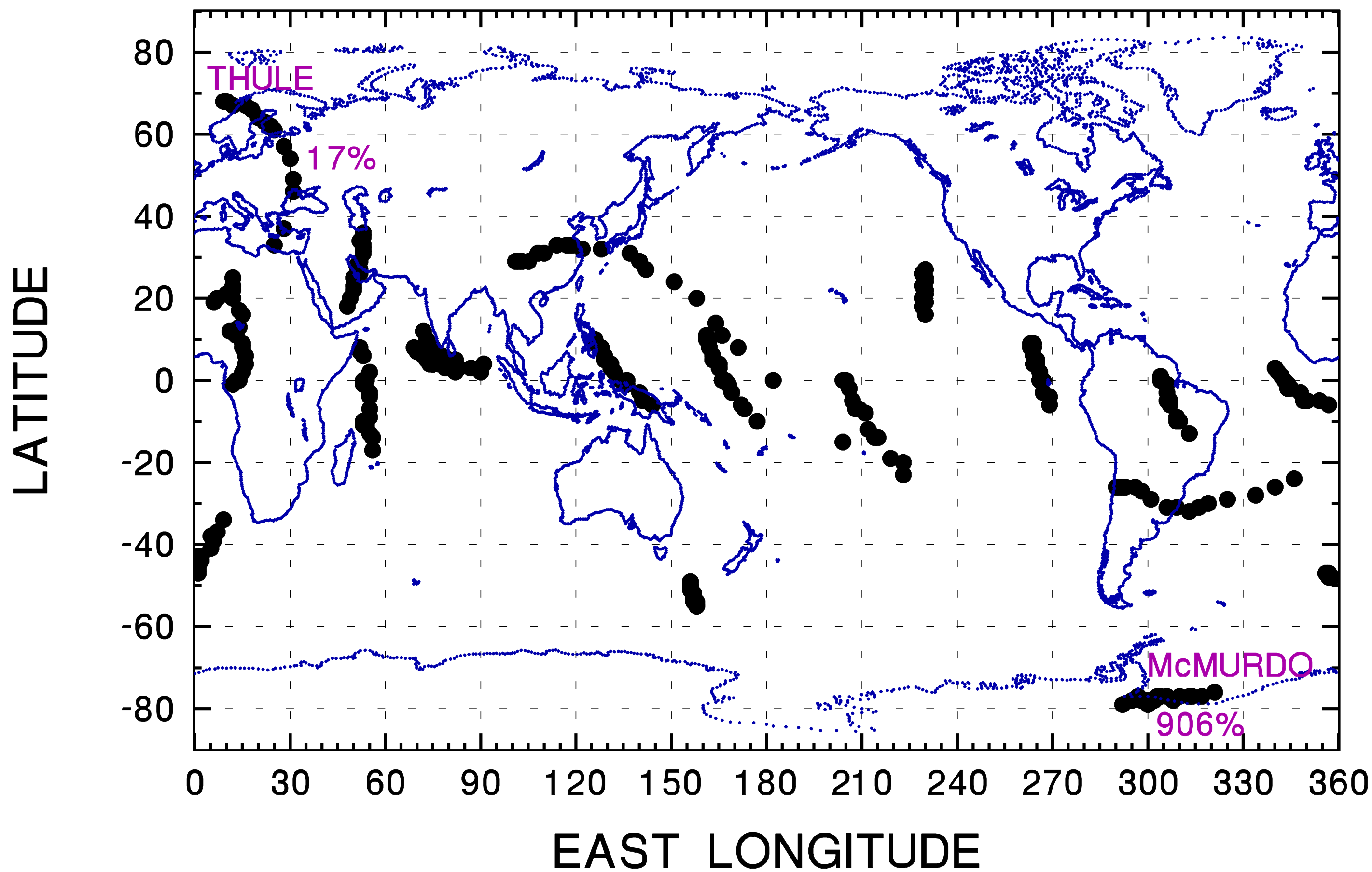
During the initial phase of a highly anisotropic event,
only those stations having their asymptotic viewing directions oriented so that they view the "forward" propagating solar particle flux
(i.e. particles having pitch angles with the interplanetary magnetic field of less than 90°)
will have a response.

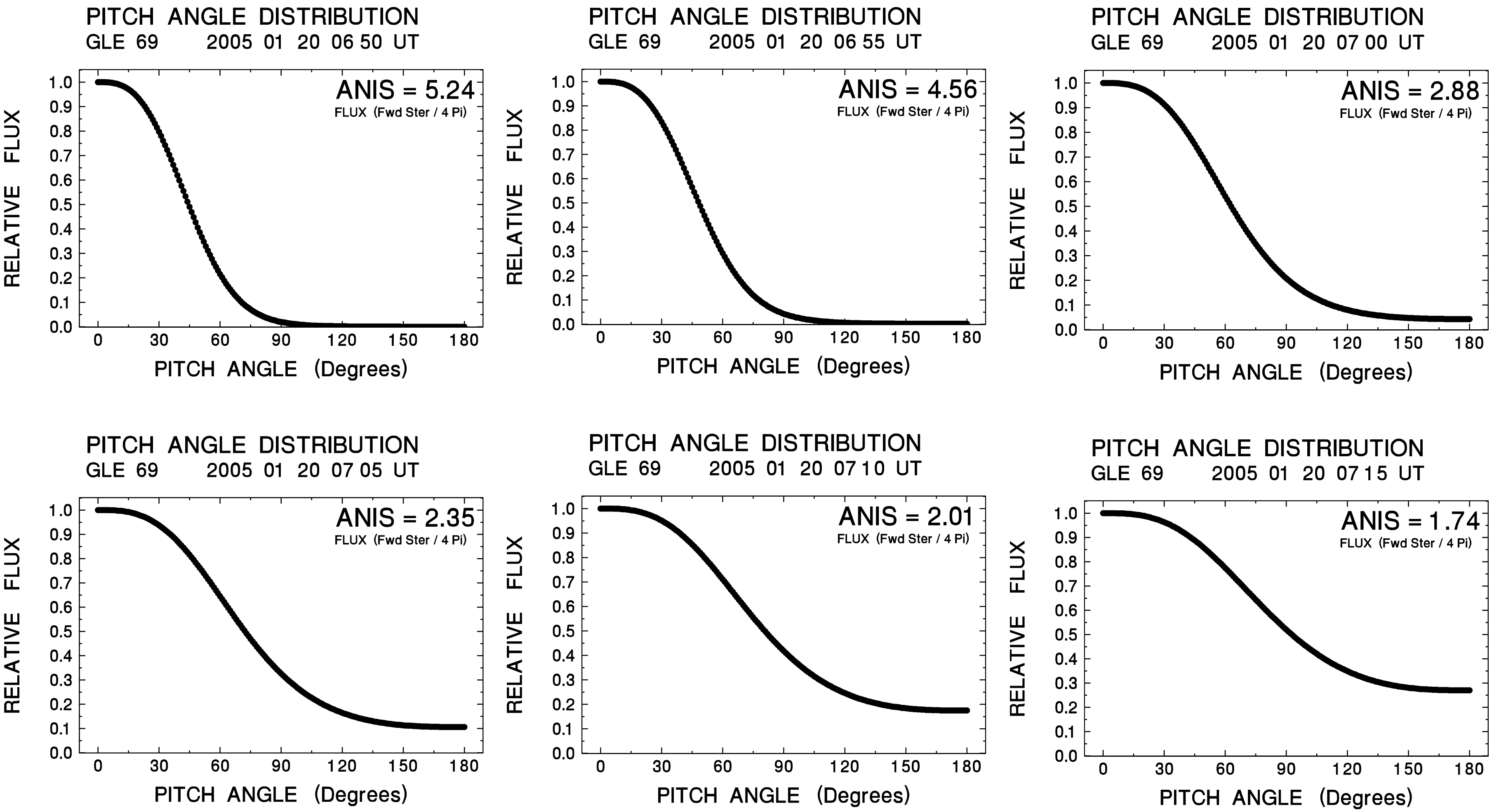
Those stations having an asymptotic cone oriented to be viewing solar particles having pitch angles > 90°
will not have a response during the initial phase of a highly anisotropic event.

As the event progresses
the pitch angle distribution will undergo more scattering,
the anisotropy will decrease,
the flux distribution will become wider, and
the high-energy solar particle event is observed world-wide.

ASYMPTOTIC DIRECTIONS

GLE 69 2005 01 20 07 00 UT

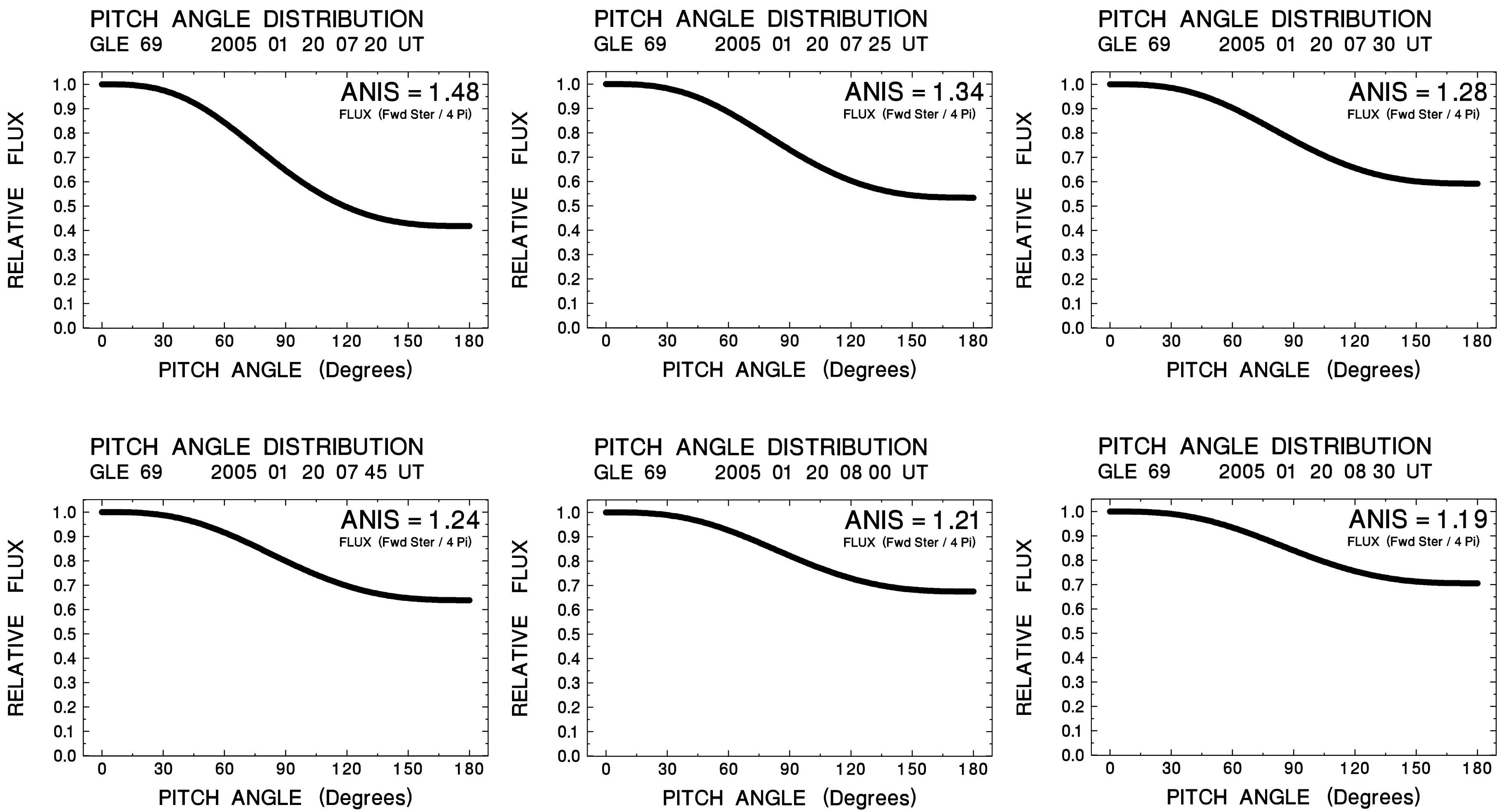




0º Pitch angle is along the IMF direction; 90º is perpendicular to the IMF direction.

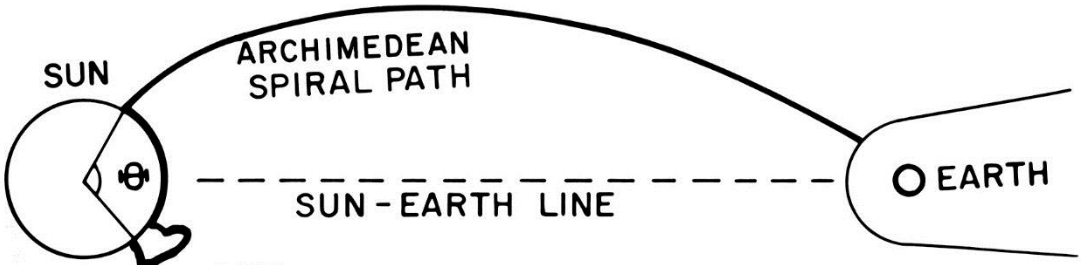
During the initial phase of a highly anisotropic GLE, only those stations oriented so that they view the "forward “propagating solar particle flux will have a response.

As the event progresses the pitch angle distribution will undergo more scattering, the anisotropy decreases, and the flux distribution becomes wider.

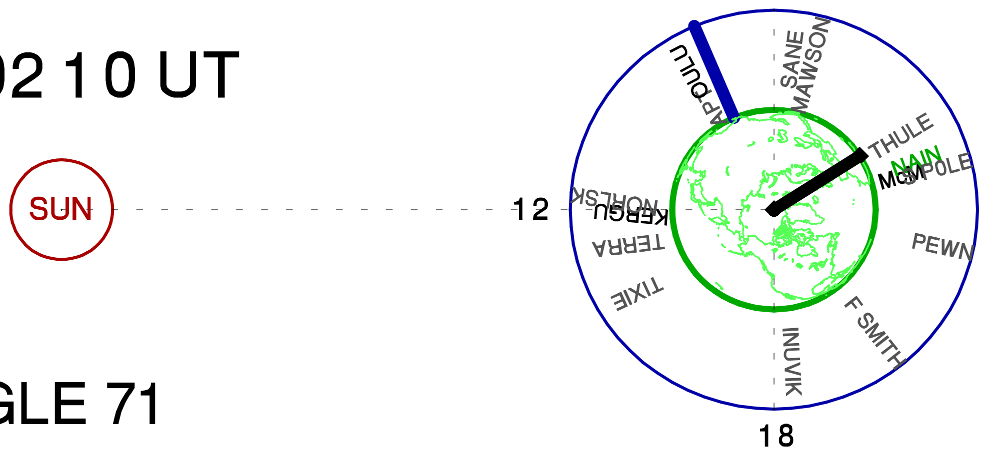


0^o Pitch angle is along the IMF direction; 90^o is perpendicular to the IMF direction. 180^o is backscatter toward the sun

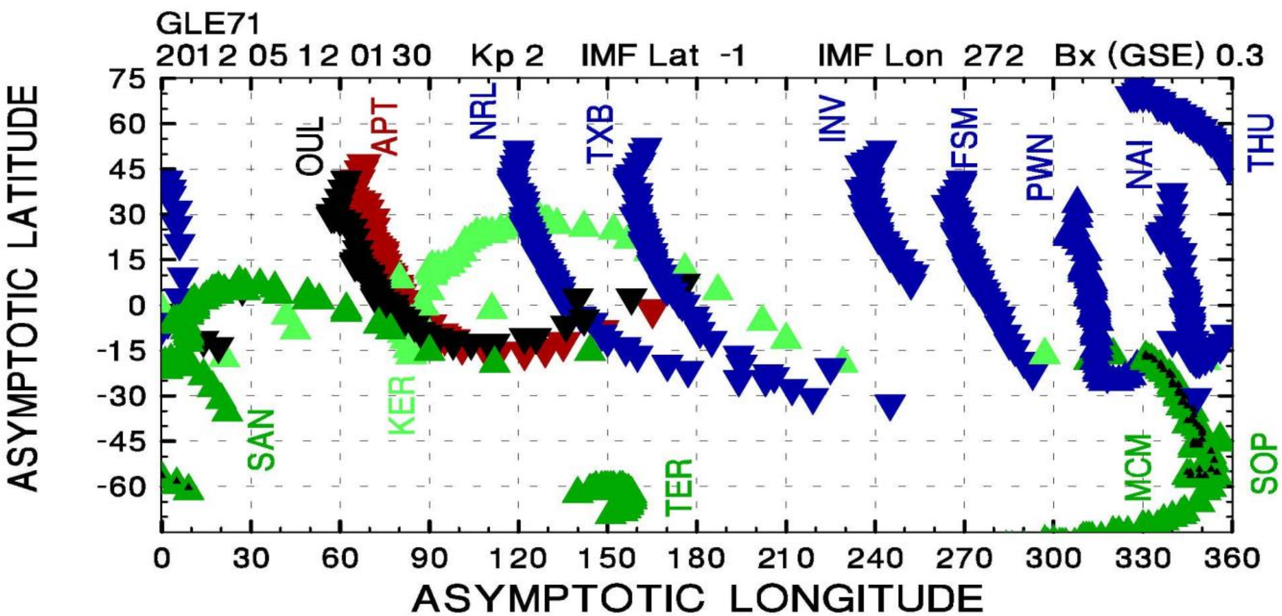
As the event progresses the pitch angle distribution will undergo more scattering, the anisotropy decreases, and the flux distribution becomes wider.

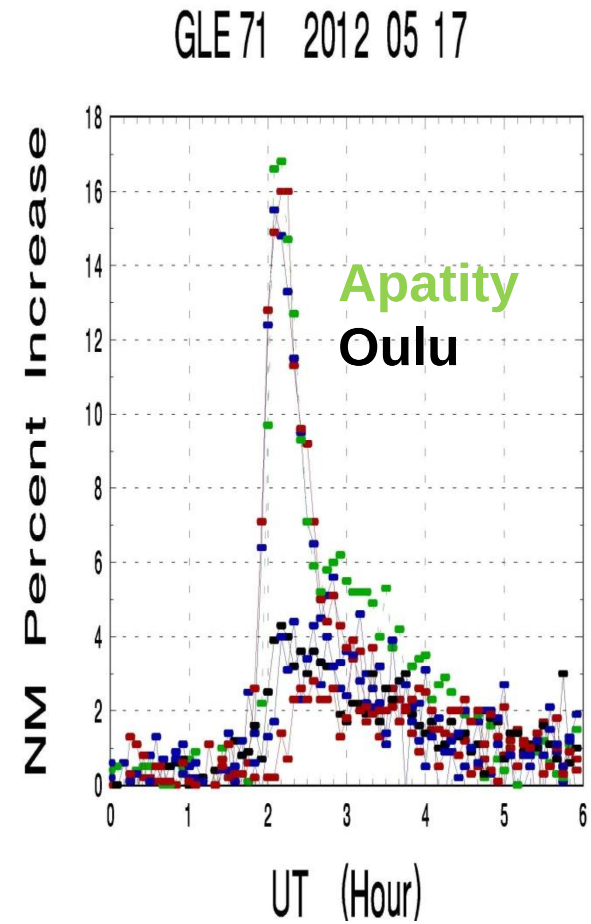


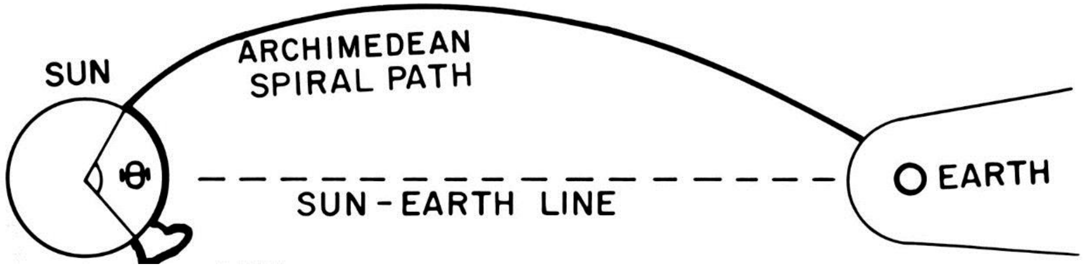
02 10 UT

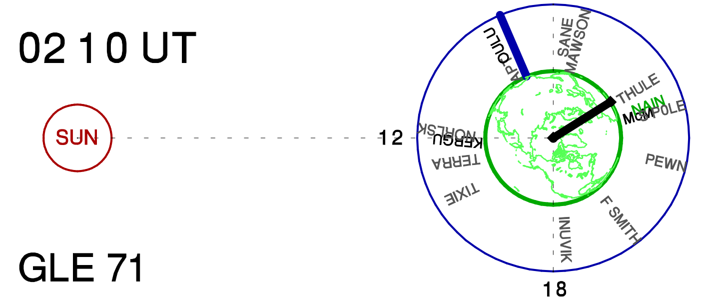


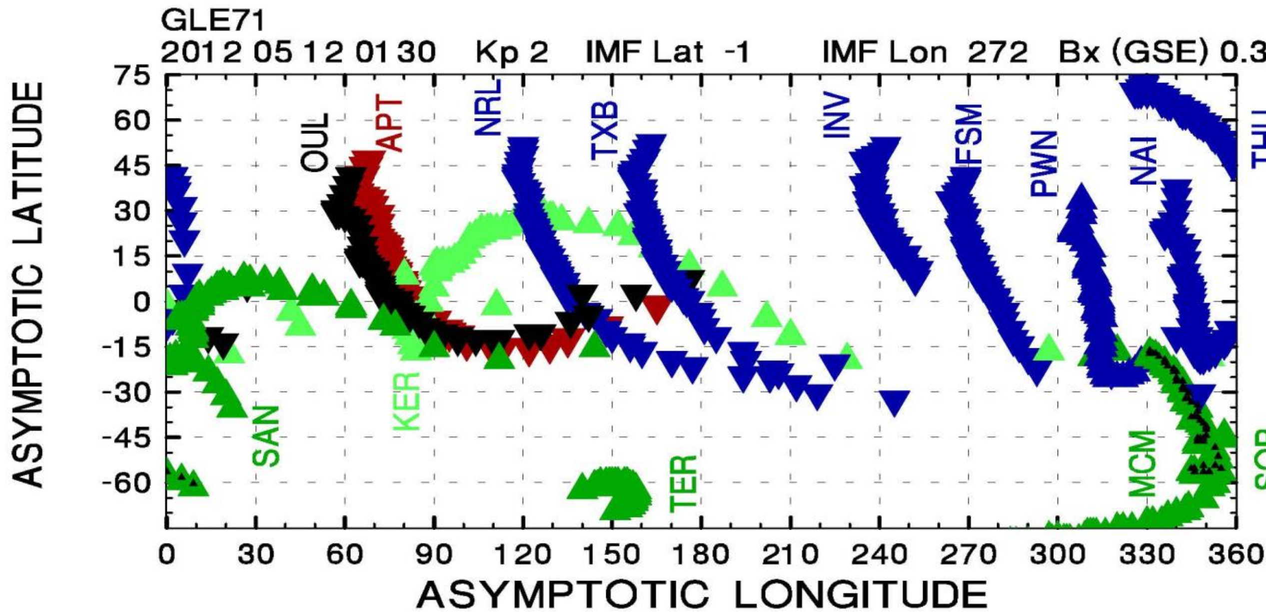
GLE 71

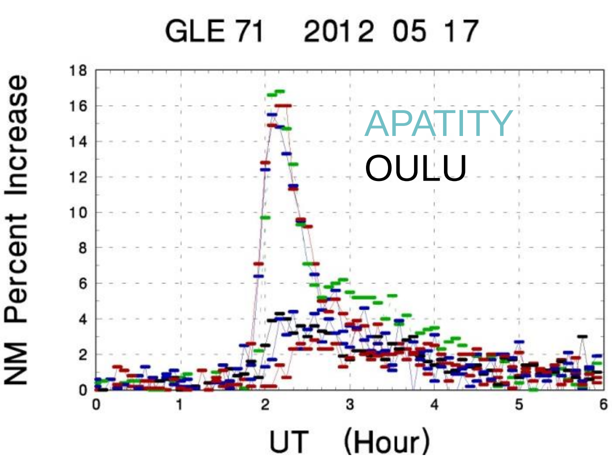


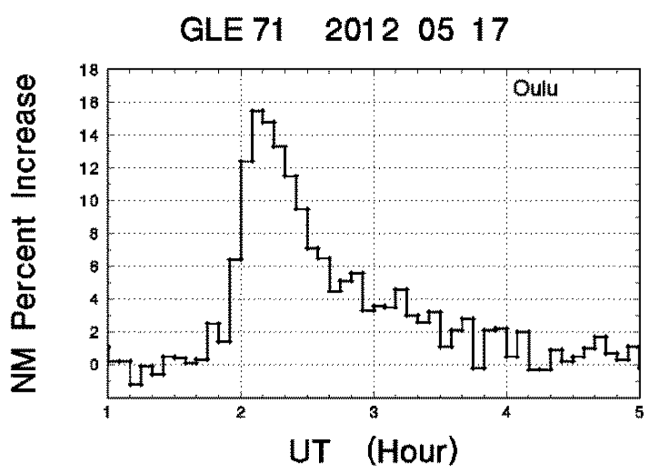


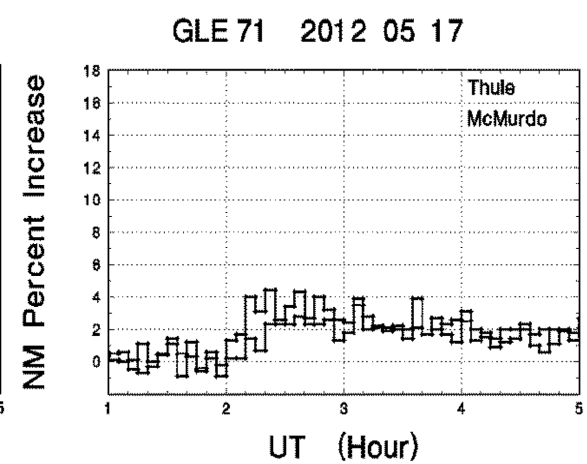

SUN
ARCHIMEDEAN SPIRAL PATH
Φ
SUN - EARTH LINE
EARTH

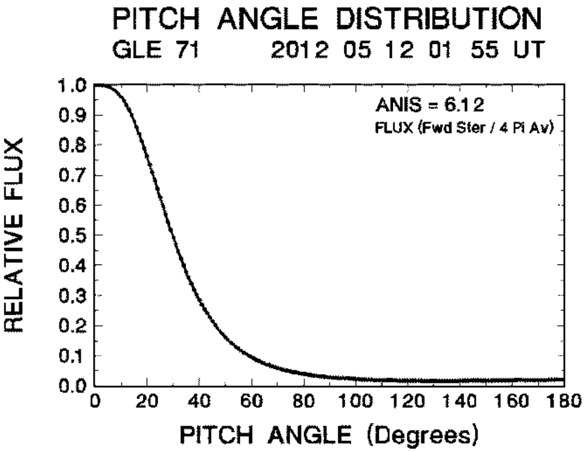

02 10 UT
SUN
12
00
18
GLE 71
APATITY
OULU
SANE
MAWSON
THULE
NAIN
McM
POLE
PEWN
F SMITH
INUVIK
TIXIE
TERRA
KERGU

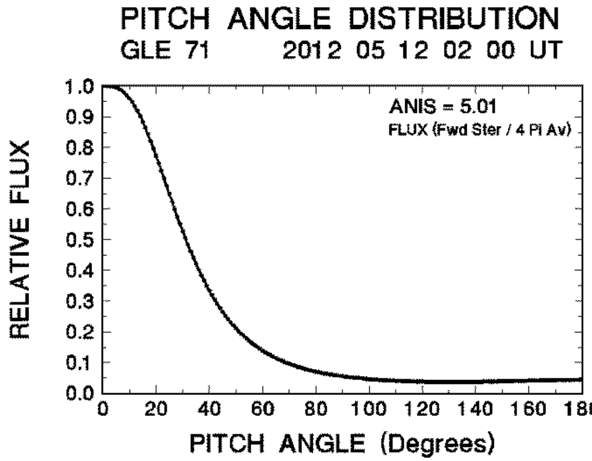

GLE71
2012 05 12 01 30 Kp 2 IMF Lat -1 IMF Lon 272 Bx (GSE) 0.3
ASYMPTOTIC LATITUDE
ASYMPTOTIC LONGITUDE
OUL
APT
NRL
TXB
INV
FSM
PWN
NAI
THU
SAN
KER
TER
MCM
SOP

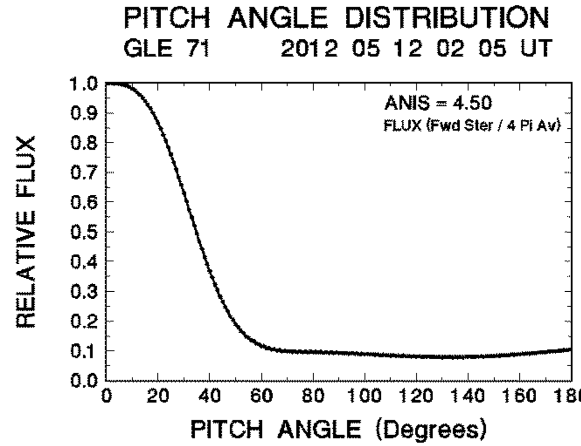

GLE 71 2012 05 17
NM Percent Increase
APATITY
OULU
UT (Hour)

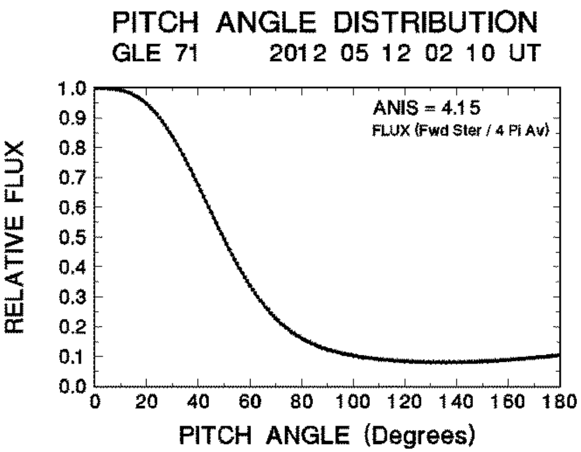

GLE 71 2012 05 17
NM Percent Increase
Oulu
UT (Hour)

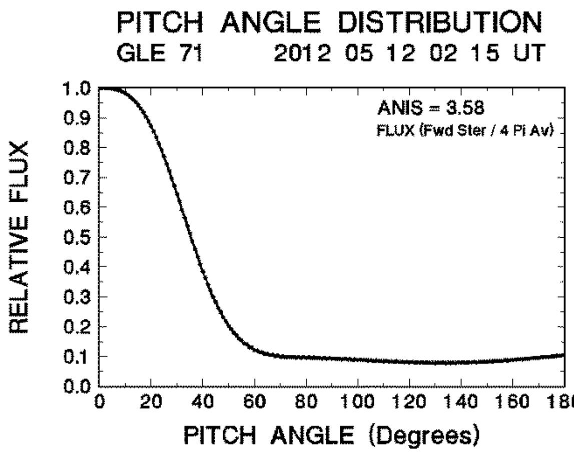

GLE 71 2012 05 17
NM Percent Increase
Thule
McMurdo
UT (Hour)

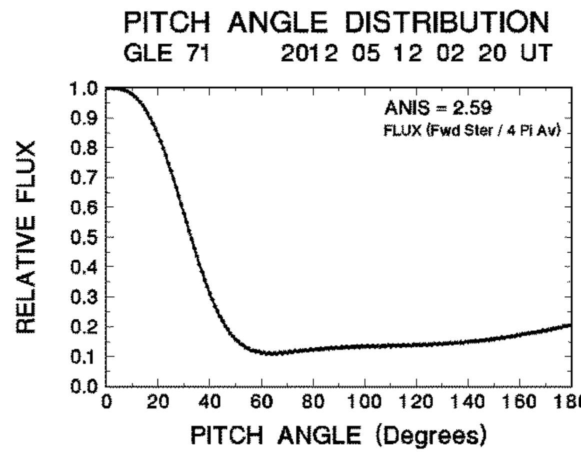

PITCH ANGLE DISTRIBUTION
GLE 71 2012 05 12 01 55 UT
ANIS = 6.12
FLUX (Fwd Ster / 4 Pi Av)
RELATIVE FLUX
PITCH ANGLE (Degrees)

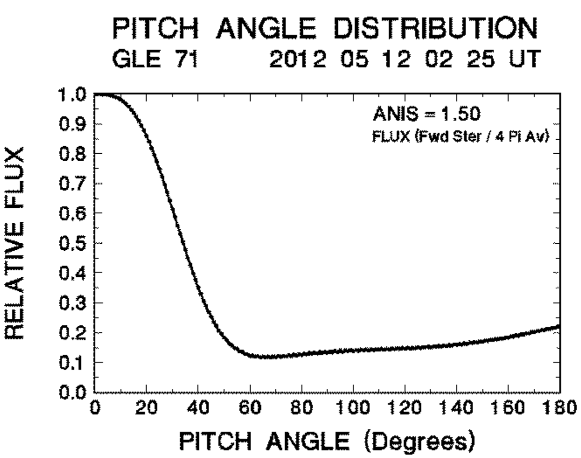

PITCH ANGLE DISTRIBUTION
GLE 71 2012 05 12 02 00 UT
ANIS = 5.01
FLUX (Fwd Ster / 4 Pi Av)
RELATIVE FLUX
PITCH ANGLE (Degrees)

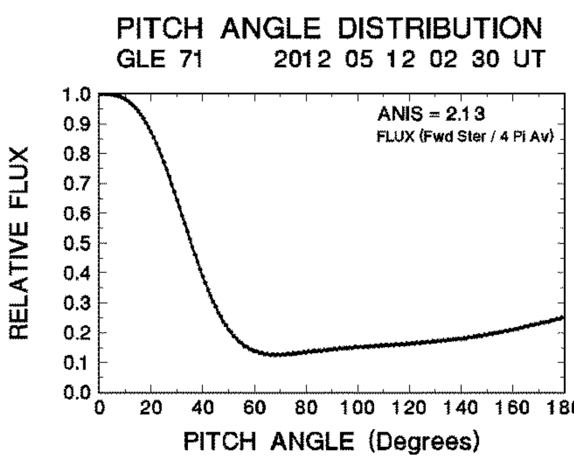

PITCH ANGLE DISTRIBUTION
GLE 71 2012 05 12 02 05 UT
ANIS = 4.50
FLUX (Fwd Ster / 4 Pi Av)
RELATIVE FLUX
PITCH ANGLE (Degrees)

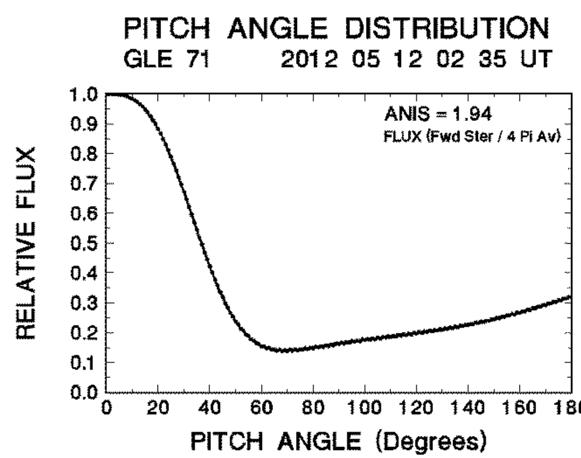

PITCH ANGLE DISTRIBUTION
GLE 71 2012 05 12 02 10 UT
ANIS = 4.15
FLUX (Fwd Ster / 4 Pi Av)
RELATIVE FLUX
PITCH ANGLE (Degrees)

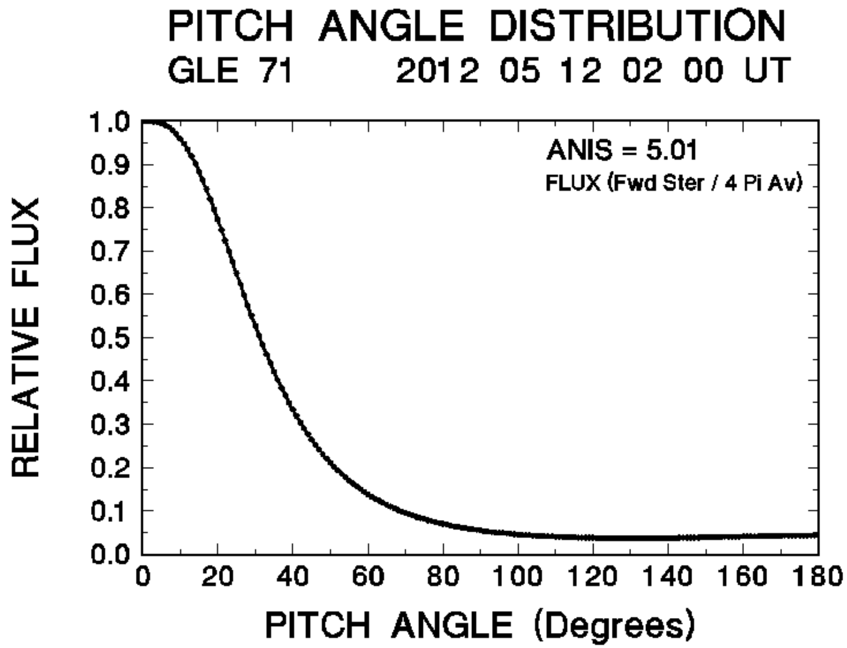

PITCH ANGLE DISTRIBUTION
GLE 71 2012 05 12 02 15 UT
ANIS = 3.58
FLUX (Fwd Ster / 4 Pi Av)
RELATIVE FLUX
PITCH ANGLE (Degrees)

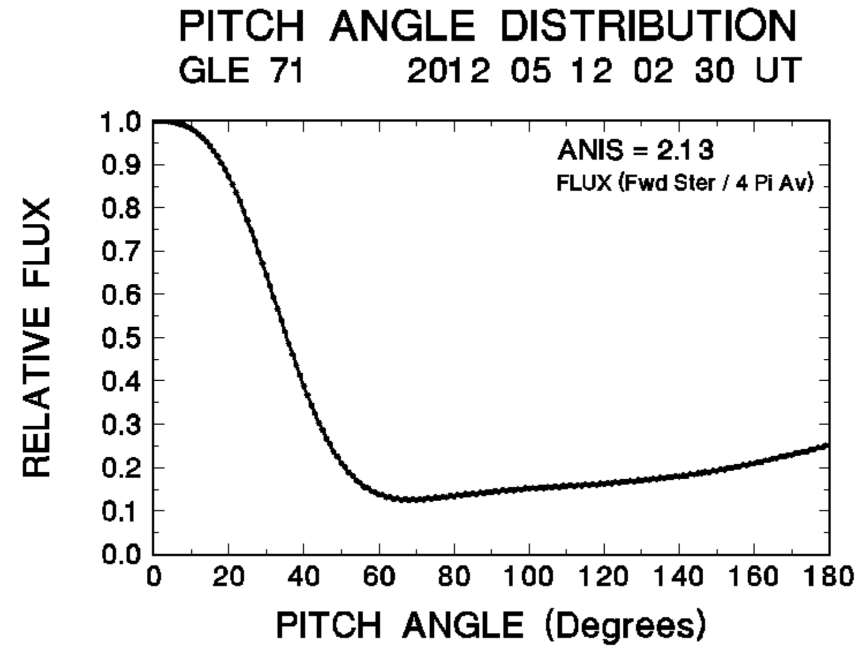

PITCH ANGLE DISTRIBUTION
GLE 71 2012 05 12 02 20 UT
ANIS = 2.59
FLUX (Fwd Ster / 4 Pi Av)
RELATIVE FLUX
PITCH ANGLE (Degrees)


PITCH ANGLE DISTRIBUTION
GLE 71 2012 05 12 02 25 UT
ANIS = 1.50
FLUX (Fwd Ster / 4 Pi Av)
RELATIVE FLUX
PITCH ANGLE (Degrees)


PITCH ANGLE DISTRIBUTION
GLE 71 2012 05 12 02 30 UT
ANIS = 2.13
FLUX (Fwd Ster / 4 Pi Av)
RELATIVE FLUX
PITCH ANGLE (Degrees)


PITCH ANGLE DISTRIBUTION
GLE 71 2012 05 12 02 35 UT
ANIS = 1.94
FLUX (Fwd Ster / 4 Pi Av)
RELATIVE FLUX
PITCH ANGLE (Degrees)


PITCH ANGLE DISTRIBUTION
GLE 71 2012 05 12 02 00 UT
ANIS = 5.01
FLUX (Fwd Ster / 4 Pi Av)
RELATIVE FLUX
PITCH ANGLE (Degrees)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GLE 71 2012 05 12 02 30 UT
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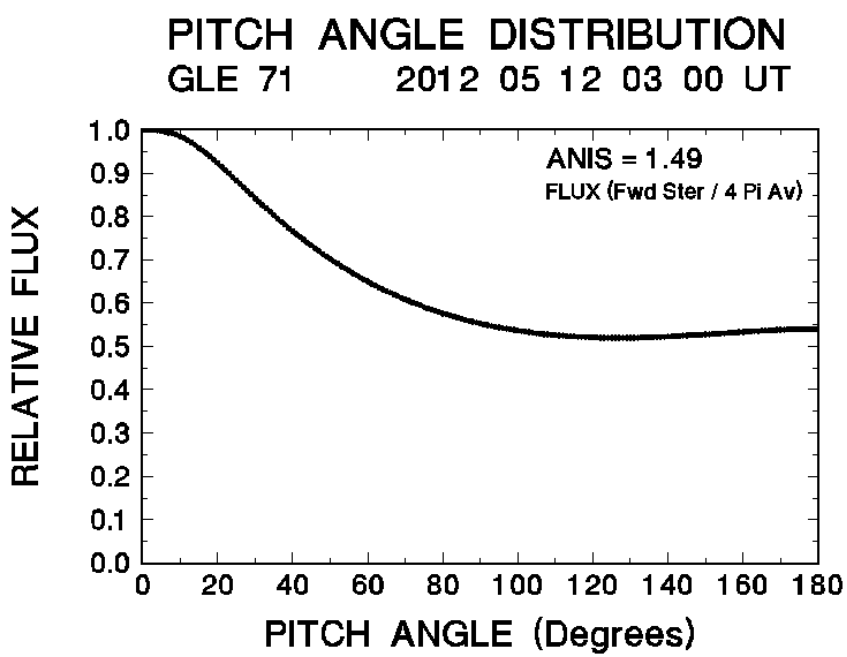
FLUX (Fwd Ster / 4 Pi Av)
RELATIVE FLUX
PITCH ANGLE (Degrees)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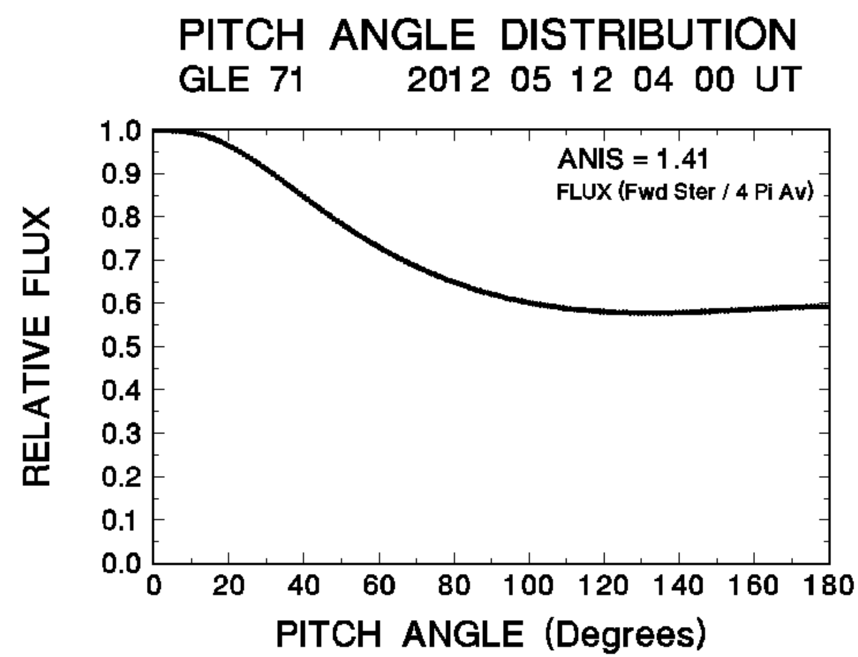
GLE 71 2012 05 12 03 00 UT
ANIS = 1.49
FLUX (Fwd Ster / 4 Pi Av)
RELATIVE FLUX
PITCH ANGLE (Degrees)


PITCH ANGLE DISTRIBUTION
GLE 71 2012 05 12 04 00 UT
ANIS = 1.41
FLUX (Fwd Ster / 4 Pi Av)
RELATIVE FLUX
PITCH ANGLE (Degrees)

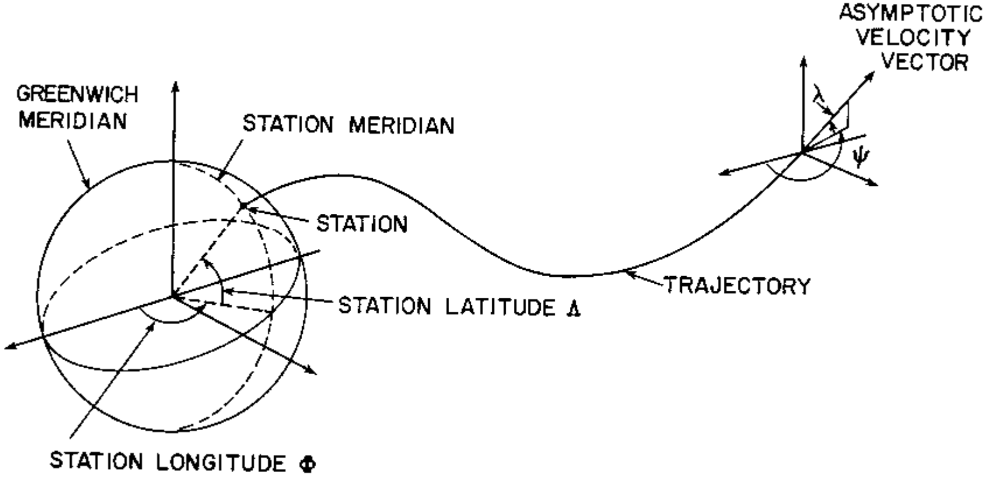
The possibility of pitch angle snapshots using AMS02 data.

AMS02 determines the **rigidity** and direction of each particle observed.
rigidity is momentum per unit charge.

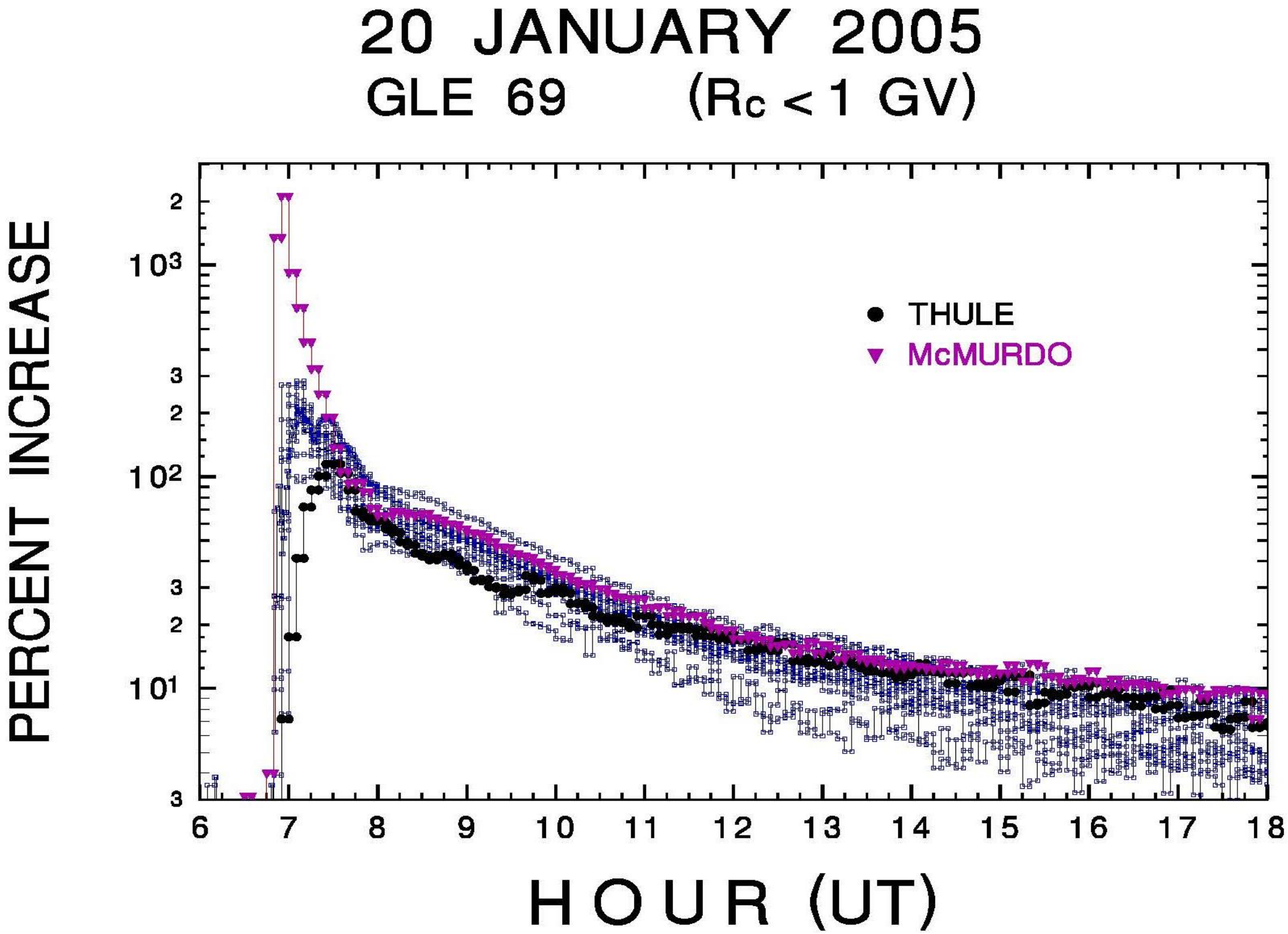
At each high-latitude pass, they can record the GLE particles allowed.

Using a magnetic field model, the trajectory can be "traced back" to establish the particle vector direction at the magnetopause boundary.

If they have the IMF vector direction (at Earth) the "dot product" of these two vectors is the pitch angle.



Extreme anisotropy is a transient phenomena. Time duration of hours or less



There will be a small persistent anisotropy as long as new fluxes are being injected into the IMF field lines.

SUMMARY

Extreme anisotropy is a transient phenomena.
Time duration of hours or less

It is difficult to predict the degree of anisotropy to be expected.

General Characteristics:

GLE's from "well connected" western hemisphere active regions normally have **large** initial anisotropies.

GLE's from central meridian active regions normally have **medium** anisotropies.

GLE's from eastern hemisphere active regions normally have **low** anisotropies.

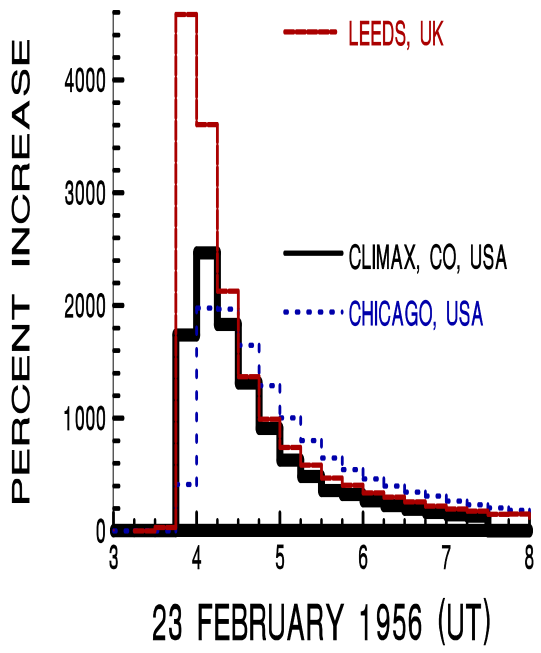
There will be a small persistent anisotropy as long as new fluxes are being injected into the IMF field lines.

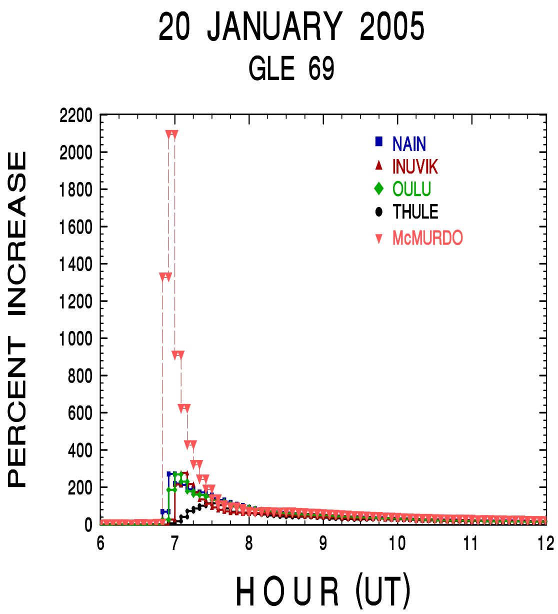
THE LARGEST OBSERVED SOLAR COSMIC RAY EVENTS

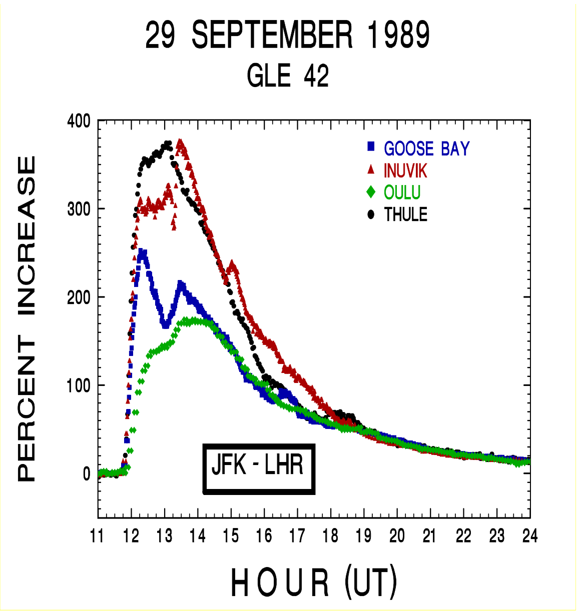
LARGEST GLE
1956 02 23
4580 % (15-min data)
Flare at 23 N, 80W

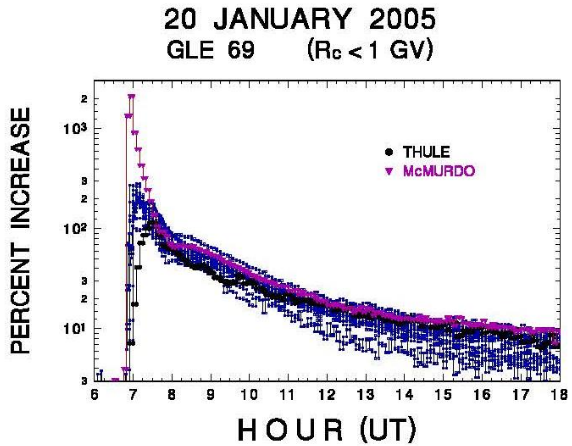
2nd LARGEST GLE
2005 01 20
2150 % (5-min data)
Flare at 14 N, 61 W

4th LARGEST GLE
1989 09 29
373 % (5-min data)
Flare at 105 W

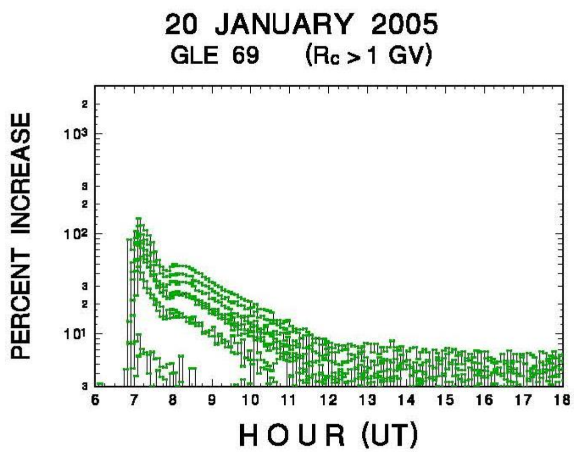








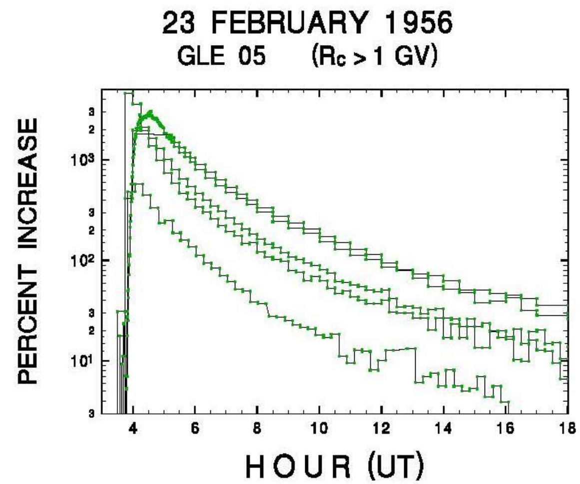
NO POLAR STATION DATA



Neutron monitor increases for GLE 69.

Highest Rigidity shown: Hermanus, Rc = 4.4 GV, ~7%

Highest Rigidity recorded: Athens, Rc = 8.4 GV, ~2%



Neutron monitor increases for GLE 05.

Highest Rigidity shown: Well., NZ, Rc = 3.4 GV

Highest Rigidity recorded in India; Muons @ 17 GV