Neutron monitor measurements

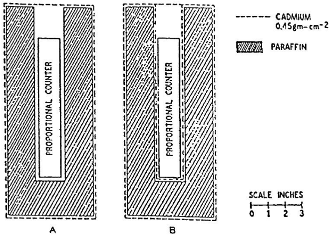
Rolf Bütikofer

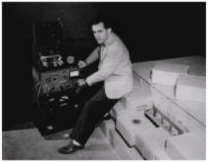
University of Bern, Switzerland and
Foundation High Altitude Research Station Jungfraujoch and Gornergrat

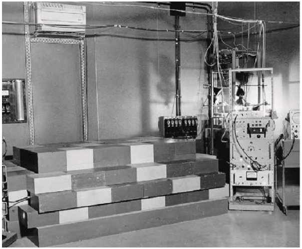
HESPERIA - Summer School
Kiel, 29 August - 2 September 2016

Invention in the 1950s

- Early neutron monitors (NMs) in the 1950s
- Network of 'Simpson' neutron monitors during IGY (1957–1958)
- Need for better statistical accuracy: In 1960s Carmichael developed 'super' or NM64 monitor







IGY NM Rome, Italy
(Storini and Signoretti, Adv. Space Res., 2009)

IGY NM Jungfraujoch, Switzerland

IGY NM Mt. Wellington, New Zealand
(McCracken et al., Adv. Space Res., 2009)

NM64 monitor Apatity, Russia

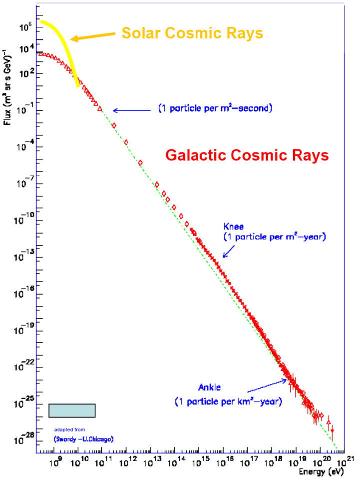
IGY neutron monitor

IGY Jungfraujoch, Switzerland

NM64 neutron monitor

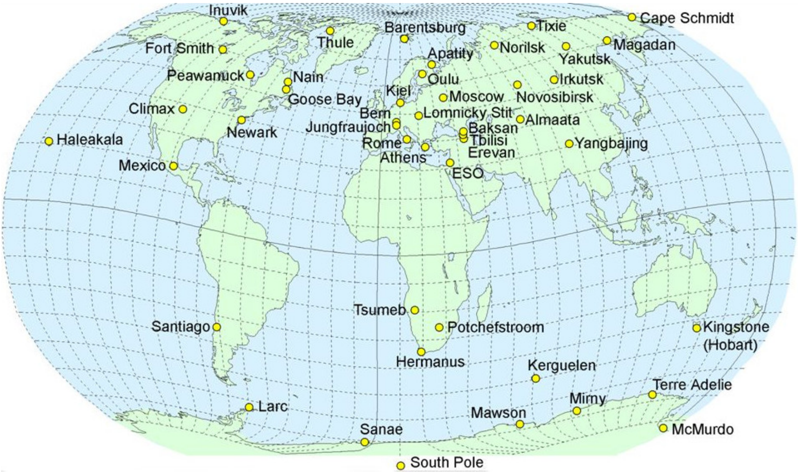
Mirny station, Antarctica

Energy spectrum of CRs and NM



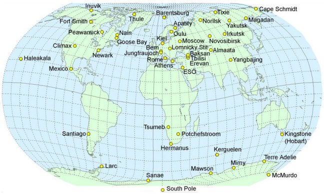
- NMs cover only energy range $\sim$ 500 MeV - 100 GeV
- But cover energy region that:
  - includes solar modulation of GCR
  - contains sporadic solar cosmic rays (SCRs)
- Have longest series of CR measurements in history (since 1956)

Worldwide network of NMs



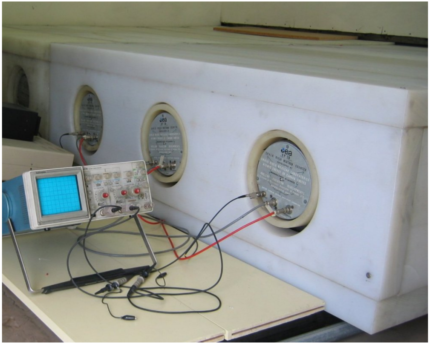
Today $\sim$ 50 NM stations in operation

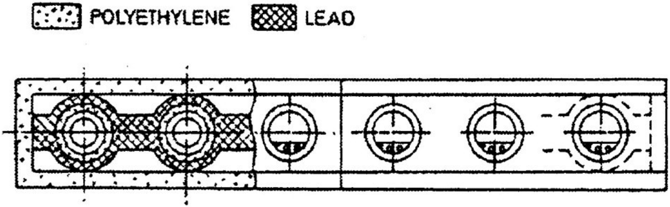
NM network = Huge spectrometer

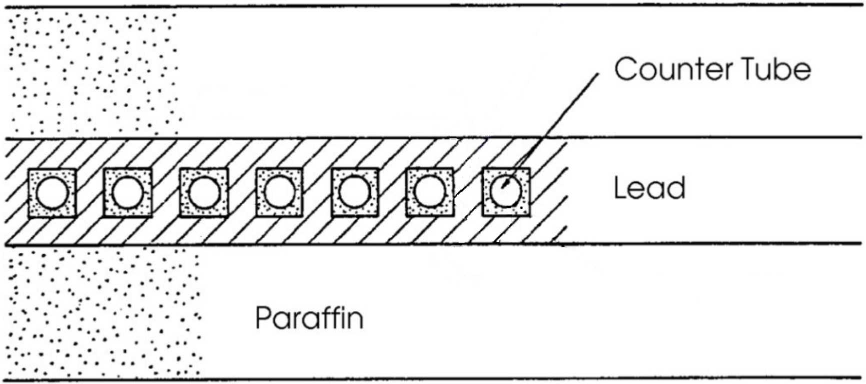


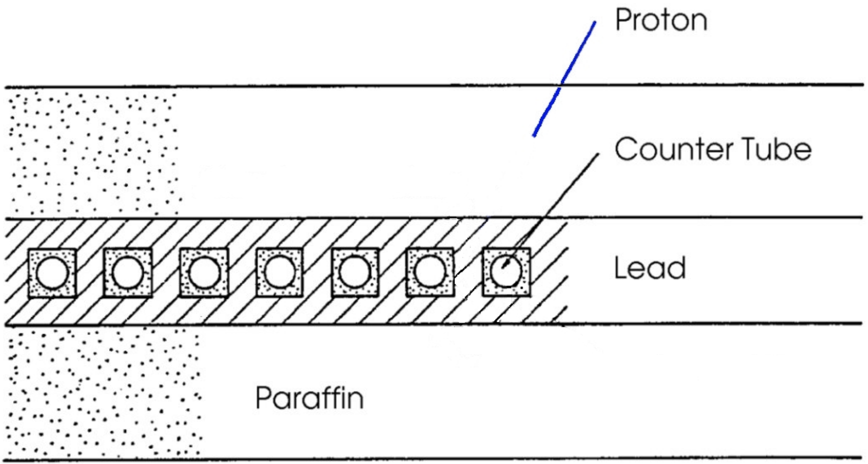
- NM stations at different geomagnetic latitudes $\rightarrow$ different cutoff rigidities $\rightarrow$ sensitive in different energy ranges $\rightarrow$ spectrometer
- NM stations located around the world $\rightarrow$ look in different directions $\rightarrow$ omni-directional detector system

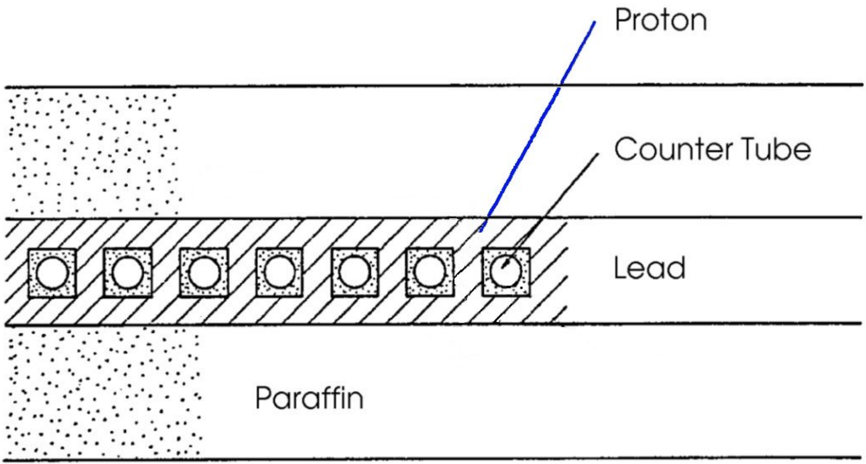
Space Ship Earth

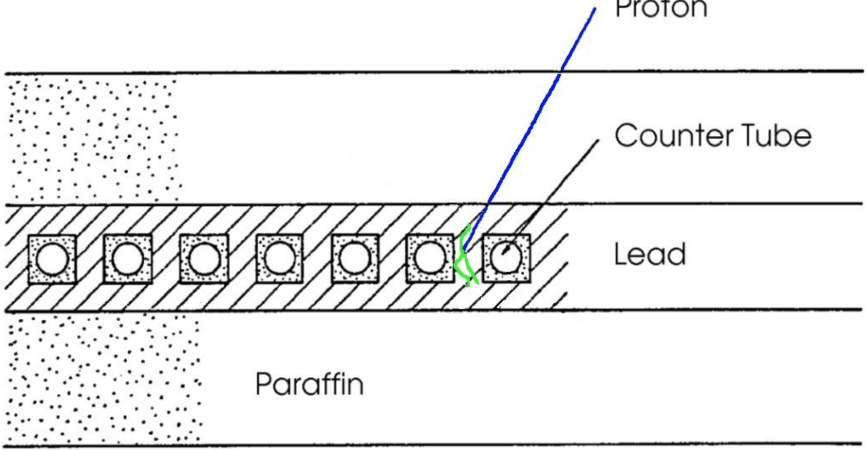


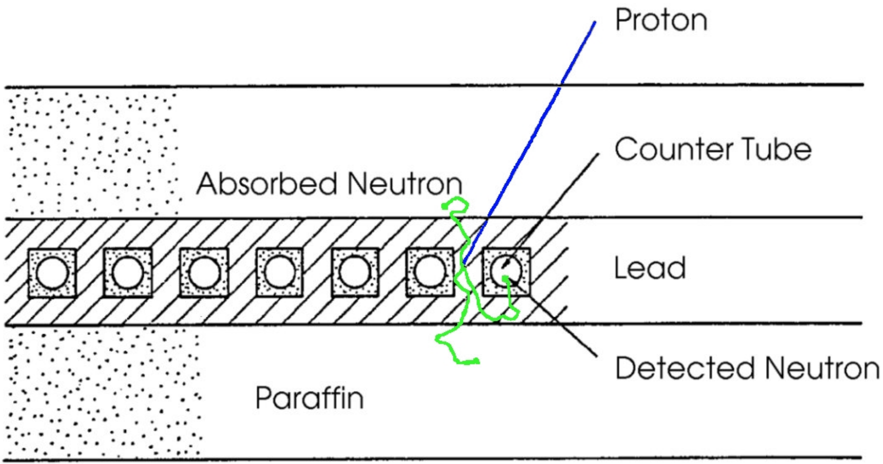

POLYETHYLENE
LEAD


Counter Tube
Lead
Paraffin


Proton
Counter Tube
Lead
Paraffin


Proton
Counter Tube
Lead
Paraffin


Proton
Counter Tube
Lead
Paraffin


Proton
Counter Tube
Absorbed Neutron
Lead
Detected Neutron
Paraffin

Counter tube I

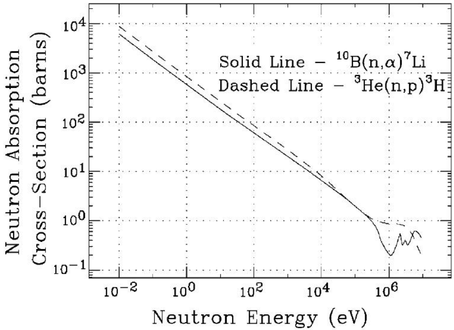
In a NM, neutron sensitive proportional tubes filled with the counter gas BF_3 are used.

They detect thermal neutrons by interaction with ^{10}B nucleus in exothermic reaction:

$$^{10}B_5 \quad + \quad n \quad \rightarrow \quad ^{7}Li_3 \quad + \quad ^{4}He_2$$

The ionisation of the counter gas by the α-particle and the Li-nucleus respectively produces electrical discharge in the counter that can be measured at the counter tube anode. Operating voltage: -2800 volts.

Counter tube II

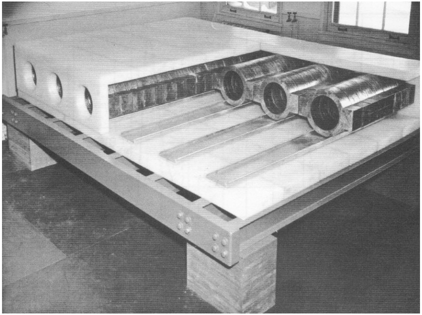


Reaction cross section as a function of neutron energy for ^{10}B and ^3He.

From Clem and Dorman, Space Sci. Rev., 2000

Neutron reaction cross-sections of ^{10}B (and ^3He) is proportional to $1/v_{neutron}$.

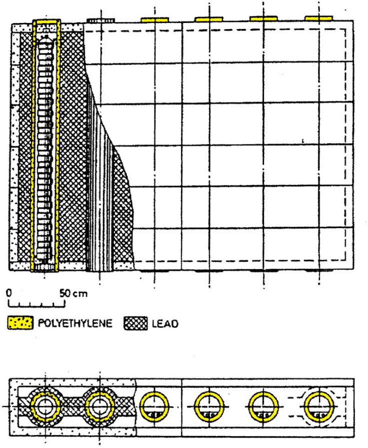
Lead producer



Task:
Production of evaporation neutrons

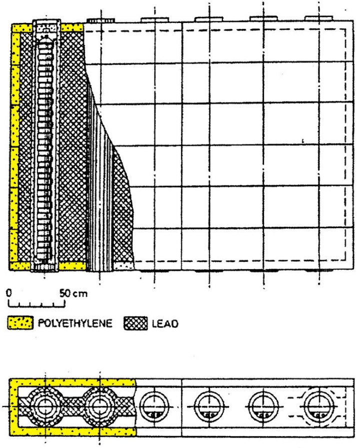
Average number of evaporation neutrons per nuclear reaction in the lead: about 15

Moderator



Task:
Slows down MeV-neutrons to near thermal energies ($\sim$1/40 eV)

Reflector



Task:

Moderates the neutrons it reflects

Absorbing and reflecting unwanted low energy neutrons produced in the atmosphere and in materials close to the monitor

Characteristics of 6-NM64 I

Geometric dimensions:	315 x 222 x 52 cm
Lead mass:	9.65 t
Polyethlene mass:	1.5 t

Floor load for a NM64 is 1’600 kg/m^2!

Characteristics of 6-NM64 II

Average count rate of a high latitude sea level 6-NM64:

count rate	stat. rel. error
$\sim$250'000 cts/h	$\sim$0.3%
$\sim$4'200 cts/min	$\sim$2.5%

The count rate of an equatorial sea level neutron monitor is $\sim$1.4 times lower.

Barometer

Multiplicity meter

Counters / Interface
Power Supply
Counters

HV Power Supplies

Counter tube

3-NM64 Jungfraujoch

NM as primary particle detector

Relationship between NM count rate and primary CR flux must be known, i.e.

- Cutoff rigidity, R_c
- Transport of cosmic rays in the atmosphere (multiple interactions, showers of secondary particles)
- Detection efficiency of NM to secondary particles (neutrons, protons, muons and pions)

Combination of transport in the atmosphere and of NM detection efficiency $\rightarrow$ Yield function

NM counting rate

$$N(R_c, z, t) = \int_{R_c}^{\infty} \sum_i S_i(R, z) \cdot J_i(R, t)\,\mathrm{d}R = \int_{R_c}^{\infty} W_T(R, z, t)\,\mathrm{d}R$$

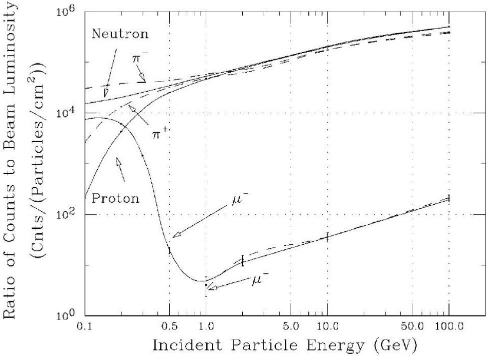
where

$N(R_c, z, t)$:	NM counting rate
R, R_c:	rigidity, geomagnetic cutoff rigidity
z:	atmospheric depth of NM station
t:	time
$S_i(R, z)$:	NM yield function for primary particle type i
$J_i(R, t)$:	differential primary particle rigidity spectrum of type i
$W_T(R, z, t)$:	total response function

Determination of yield function

- Latitude survey: fitting a chosen function to the count rate during a latitude survey
- Theoretical calculation method: attempts to quantify all fundamental physical mechanisms
- Monte Carlo method: simulation of particle interactions in atmosphere and detector
- Neutron monitor in accelerator neutron beam

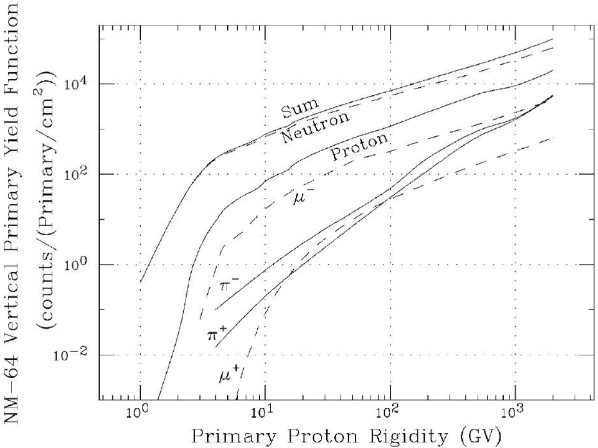
Detection efficiency for secondary particles



Clem and Dorman, Space Sci. Rev., 2000

Calculated NM64 detection efficiency for secondary particles arriving in vertical direction

Yield function



Clem and Dorman, Space Sci. Rev., 2000

Calculated yield function of NM64 monitor at sea level from vertical incident primary protons

Contribution of secondary CR components to total counting rate

Component	Contribution [%]
Neutrons	85
Protons	7
Muons	6
Pions	1
Background	1

Count rate of a NM station

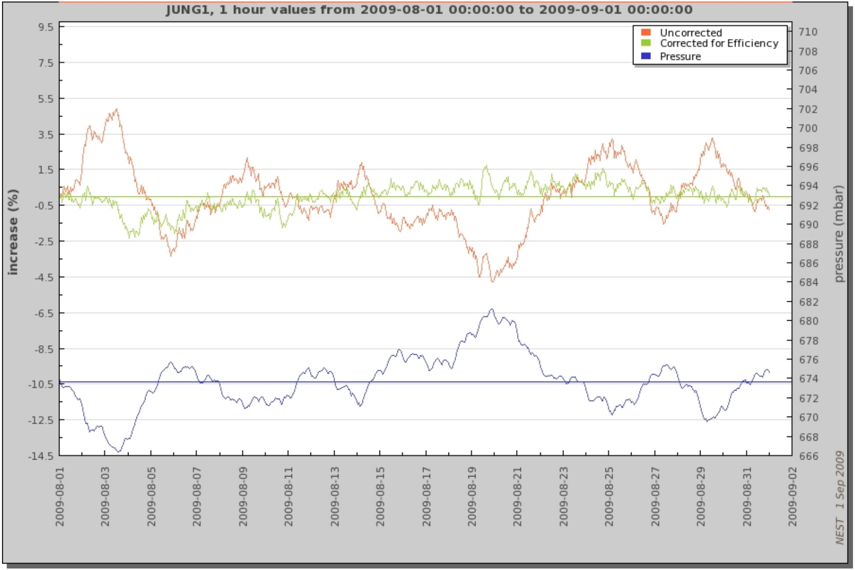
$$N_{StA}(t) = A_{StA} \cdot \int_{P_c^{StA}}^{\infty} S(P, z = z_{StA}) \cdot J(P, t) \, \mathrm{d}P$$

$$\begin{aligned}
\Delta N_{StA}(t) &= N_{StA}(t) - N_{StA}(t_0) \\
&= A_{StA} \cdot \int_{P_c^{StA}}^{\infty} S(P, z = z_{StA}) \cdot (J(P, t) - J(P, t_0)) \, \mathrm{d}P
\end{aligned}$$

Effects on counting rates

- Meteorological effects (atmospheric mass, temperature)
- Environmental effects (snow, housing)
- Longterm stability of NMs
- Instrumental effects (drifts, tube aging)

Effect of the atmospheric mass I



Effect of the atmospheric mass II

- Change in the mass of air above the monitor has a large effect on the counting rate
- This change is the only significant meteorologic factor (temperature effect 0.03% / $^{\circ}$C)
- Barometric pressure is used as a proxy for the air mass above the NM station

Effect of the atmospheric mass III

Barometric Corrections:

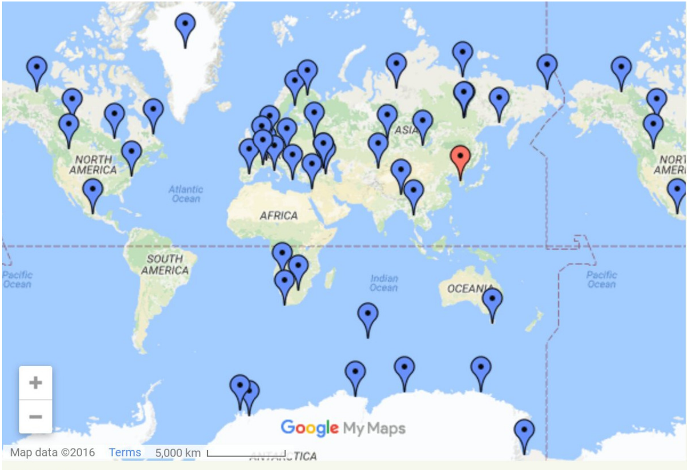
$$N(p_0) = N(p(t)) \cdot e^{\alpha(p(t)-p_0)}$$

where:

N:	count rate,
p_o:	reference pressure ($p_0 = 1013$ mbar),
$p(t)$:	pressure at time t,
α:	pressure coefficient ($\alpha \approx 0.0072$ mbar^{-1})

Change of barometric pressure by 1 mmHg causes a change of $\sim$1% in the count rate

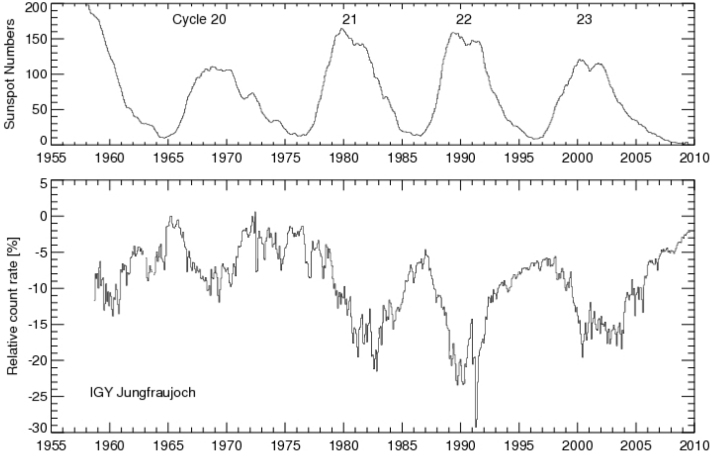
Worldwide network of NM stations



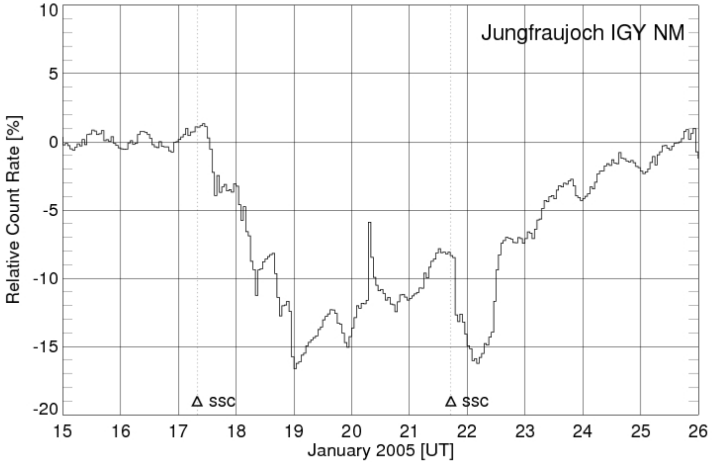
Neutron Monitor Database (NMDB)

www.nmdb.eu

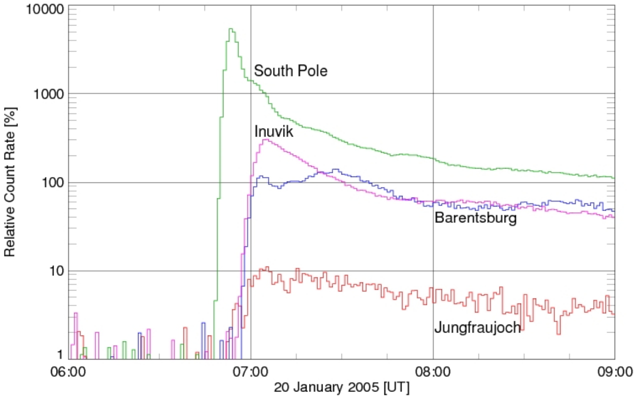
11-year modulation



Forbush decrease



Solar cosmic ray event



Solar Energetic Particle (SEP) event, Solar Proton Event (SPE), Ground Level Enhancement (GLE)

Take home message

- Energy range covered by NMs?
- This energy region includes?

- Main contribution of secondary CR components to total counting rate?

- From where are NM data available?
- Effects that can be observed by NMs?

Take home message

- Energy range covered by NMs? $\sim$ 500 MeV - 100 GeV
- This energy region includes?
- Main contribution of secondary CR components to total counting rate?
- From where are NM data available?
- Effects that can be observed by NMs?

Take home message

- Energy range covered by NMs? ~ 500 MeV - 100 GeV
- This energy region includes?

- Main contribution of secondary CR components to total counting rate?

- From where are NM data available?
- Effects that can be observed by NMs?

Take home message

- Energy range covered by NMs? $\sim$ 500 MeV - 100 GeV
- This energy region includes? Solar modulation of GCR
- Main contribution of secondary CR components to total counting rate?
- From where are NM data available?
- Effects that can be observed by NMs?

Take home message

- Energy range covered by NMs? $\sim$ 500 MeV - 100 GeV
- This energy region includes? Solar modulation of GCR and sporadic SCR
- Main contribution of secondary CR components to total counting rate?

- From where are NM data available?
- Effects that can be observed by NMs?

Take home message

- Energy range covered by NMs? $\sim$ 500 MeV - 100 GeV
- This energy region includes? Solar modulation of GCR and sporadic SCR
- Main contribution of secondary CR components to total counting rate?
- From where are NM data available?
- Effects that can be observed by NMs?

Take home message

- Energy range covered by NMs? $\sim$ 500 MeV - 100 GeV
- This energy region includes? Solar modulation of GCR and sporadic SCR
- Main contribution of secondary CR components to total counting rate? neutrons 85%,
- From where are NM data available?
- Effects that can be observed by NMs?

Take home message

- Energy range covered by NMs? $\sim$ 500 MeV - 100 GeV
- This energy region includes? Solar modulation of GCR and sporadic SCR
- Main contribution of secondary CR components to total counting rate? neutrons 85%, protons 7%, muons 6%, pions 1%
- From where are NM data available?
- Effects that can be observed by NMs?

Take home message

- Energy range covered by NMs? $\sim$ 500 MeV - 100 GeV
- This energy region includes? Solar modulation of GCR and sporadic SCR
- Main contribution of secondary CR components to total counting rate? neutrons 85%, protons 7%, muons 6%, pions 1%
- From where are NM data available?
- Effects that can be observed by NMs?

Take home message

- Energy range covered by NMs? $\sim$ 500 MeV - 100 GeV
- This energy region includes? Solar modulation of GCR and sporadic SCR
- Main contribution of secondary CR components to total counting rate? neutrons 85%, protons 7%, muons 6%, pions 1%
- From where are NM data available? www.nmdb.eu
- Effects that can be observed by NMs?

Take home message

- Energy range covered by NMs? $\sim$ 500 MeV - 100 GeV
- This energy region includes? Solar modulation of GCR and sporadic SCR
- Main contribution of secondary CR components to total counting rate? neutrons 85%, protons 7%, muons 6%, pions 1%
- From where are NM data available? www.nmdb.eu
- Effects that can be observed by NMs?

Take home message

- Energy range covered by NMs? $\sim$ 500 MeV - 100 GeV
- This energy region includes? Solar modulation of GCR and sporadic SCR
- Main contribution of secondary CR components to total counting rate? neutrons 85%, protons 7%, muons 6%, pions 1%
- From where are NM data available? www.nmdb.eu
- Effects that can be observed by NMs? 11-year modulation,

Take home message

- Energy range covered by NMs? $\sim$ 500 MeV - 100 GeV
- This energy region includes? Solar modulation of GCR and sporadic SCR
- Main contribution of secondary CR components to total counting rate? neutrons 85%, protons 7%, muons 6%, pions 1%
- From where are NM data available? www.nmdb.eu
- Effects that can be observed by NMs? 11-year modulation, Forbush decrease,

Take home message

- Energy range covered by NMs? $\sim$ 500 MeV - 100 GeV
- This energy region includes? Solar modulation of GCR and sporadic SCR
- Main contribution of secondary CR components to total counting rate? neutrons 85%, protons 7%, muons 6%, pions 1%
- From where are NM data available? www.nmdb.eu
- Effects that can be observed by NMs? 11-year modulation, Forbush decrease, solar cosmic ray events (GLE)