Particle Astrophysics

Harm Moraal

North-West University
Potchefstroom

SAIP Conference, 8 July 2014
Topics

• South African astronomy
• Particle vs. photon astronomy
• Cosmic-ray spectra, composition
• Dark matter
• Neutrinos
• Cosmic-ray variations
• “Cosmic” rays from the sun
• Helioclimatology
“The Skies” are explored through

• Photons
  - Radio
  - Microwave
  - Infrared
  - Optical
  - X-ray
  - Gamma ray

• Particles
ASTRONOMY IN SOUTH AFRICA:
A MULTI-WAVELENGTH LONG-TERM STRATEGIC PLAN

Astronomy Desk Draft – version 1
28 May 2014
Multiwavelength Astronomy

Radio: $10^4$, Microwave: $10^2$, Infrared: $10^{-3}$, Visible: $10^{-5}$, Ultraviolet: $10^{-6}$, X-ray: $10^{-7}$, Gamma Ray: $10^{-10}$, $10^{-12}$

Wavelength in Meters

About the size of...
Multiwavelength Astronomy

SAAO & SALT
Multiwavelength Astronomy

Hart RAO & KAT, MeerKAT, SKA

SAAO & SALT
Multiwavelength Astronomy

Hart RAO & KAT, MeerKAT, SKA
SAAO & SALT
H.E.S.S
Multiwavelength Astronomy

Hart RAO & KAT, MeerKAT, SKA
SAAO & SALT
H.E.S.S

CTA, end 2014?
Multiwavelength Astronomy

Energy $= \frac{hc}{\lambda}$

- $< 10^{-3}$ eV
- $\sim 1$ eV
- $> 10^9$ eV
Multiwavelength Astronomy

Energy = $\frac{hc}{\lambda}$

$< 10^{-3}$ eV
Rotations and vibrations

$\sim 1$ eV
Electronic jumps

$> 10^9$ eV
Nuclear reactions
Multiwavelength Astronomy

- Hart RAO & KAT, MeerKAT, SKA
- SAAO & SALT
- H.E.S.S

- Horsehead nebula
- Galaxy M31
- Active Galactic Nucleus (guess)
Topics

- South African astronomy
- **Particle vs. photon astronomy**
- Cosmic-ray spectra, composition
- Dark matter
- Neutrinos
- Cosmic-ray variations
- “Cosmic” rays from the sun
- Helioclimatology
Cosmic rays

- Charged particles - 90% protons, 5% He nuclei, 3% heavier atomic nuclei, 2% electrons

- Characterised by very high energies ($10^6$ - $10^{20}$ eV)
Victor Hess, 7 August 1912
Particle vs. Photon Astronomy

Photons

1. Where
2. How bright
3. Colour
Particle vs. Photon Astronomy

- Photons
  1. Where
  2. How bright
  3. Colour
Particle vs. Photon Astronomy

Particles:
No such information
Because of magnetic fields

Photons
1. Where
2. How bright
3. Colour
Charged particles spiral around magnetic field lines
Kinks in field cause scattering

This way?

Other way?

No way...? stuck
Particle vs. Photon Astronomy

Particles:
No such information
Because of magnetic fields

......like a bead on an elastic band

Photons

1. Where
2. How bright
3. Colour
Particle vs. Photon Astronomy

Photons

1. Where
2. How bright
3. Colour
**Particle vs. Photon Astronomy**

**Particles:**
No such information
Because of magnetic fields

......like a bead on an elastic band

**Photons**
1. Where
2. How bright
3. Colour
Charged particles in magnetic fields

 scattering → isotropy
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Cosmic ray spectrum

Fluxes of Cosmic Rays

(1 particle per m²-second)

Knee
(1 particle per m²-year)

Ankle
(1 particle per km²-year)

N  Number of particles

Energy (eV)
Cosmic-ray spectrum

Fluxes of Cosmic Rays

N (Number of particles)

Energy (eV)

Cricket Ball

Ankle (1 particle per km²-year)

Knee (1 particle per m²-year)

(1 particle per m²-second)
Cosmic-ray spectrum

Energy (eV)

Number of particles

 Fluxes of Cosmic Rays

(1 particle per m²-second)

Highest Energy at CERN

(1 particle per m²-year)

Cricket Ball

Ankle

(1 particle per km²-year)
Cosmic ray spectrum

Power law: $N = a E^{-2.5}$

$log N = -2.5 \log E + \log a$
Cosmic-ray spectrum

Thermal Maxwell-Boltzmann spectrum

\[ f(v) \propto v^2 e^{-mv^2/2kT} \; ; \; f(E) = E e^{-E/kT} \]
Cosmic-ray spectrum

Thermal Maxwell-Boltzmann spectrum

\[ f(v) \propto v^2 e^{-mv^2/2kT}; \quad f(E) = E e^{-E/kT} \]
Cosmic-ray spectrum

Thermal Maxwell-Boltzmann spectrum

\[ f(v) \propto v^2 e^{-mv^2/2kT} \]

\[ f(E) = E e^{-E/kT} \]
Cosmic ray spectrum

Power law: \( N = a E^{-2.5} \)

\[ \log N = -2.5 \log E + \log a \]
Cosmic-ray spectrum

Thermal Maxwell-Boltzmann spectrum

\[ f(v) \propto v^2 e^{-mv^2/2kT} ; \quad f(E) = E e^{-E/kT} \]
Cosmic-ray spectrum

Thermal Maxwell-Boltzmann spectrum

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Cosmic-ray spectrum

Thermal Maxwell-Boltzmann spectrum:

\[ f(v) \propto v^2 e^{-mv^2/2kT}; \quad f(E) = E e^{-E/kT} \]

Shocks can do this (1977)

Energy (eV)
Cassiopeia A in X-rays
Solar Atmosphere
Solar Wind
Solar Wind

- Supersonic 400 km/s
- Sound (Alfvén) speed 40 km/s
- Mach 10
- Low energy ($T \sim 10^6$ K, $E < 10$ KeV)
The Heliosphere

Standing shock ~ 150 Astronomical Units (AU)

$V_{\text{wind}} \sim 400 \text{ km/s}$

$V_{\text{sound}} \sim 40 \text{ km/s}$

~ 150 Astronomical Units (AU)
The Heliosphere

- Sun
- Termination Shock
- Bow Shock
- Heliospause
- Heliosheath
The Heliosphere
The Heliosphere

Bow shock
Geomagnetic field

Standing shock
Moving shocks
Moving shocks
Moving shocks
The kitchen sink (standing shock)
Stationary shock; kitchen sink

Unshocked

Shocked
Moving shocks

Shocked

Unshocked

Shocked

Unshocked
• A flow is supersonic (super Alfvénic) when it is faster than the particles can interact with each other

• This supersonic flow can only become subsonic through a shock transition
Cosmic-ray spectrum

Thermal Maxwell-Boltzmann spectrum

\[ f(v) \propto v^2 e^{-mv^2/2kT}; \quad f(E) = E e^{-E/kT} \]

Shock acceleration
Acceleration
Acceleration
Acceleration
Acceleration
Acceleration

Upstream: $V_1$

Downstream: $V_2 < V_1$

Shock = net
Acceleration

Shock = net

$V_2 < V_1$
Acceleration

\[ \text{Shock} = \text{net} \]

\[ V_2 < V_1 \]

Spiral
Diffusive shock acceleration (1977)

\[ n(E) = aE^{\frac{2+s}{1-s}} \]

where \( s = \frac{V_1}{V_2} = \frac{\rho_2}{\rho_1} \) = compression ratio

Maximum \( s = 4 \) (this follows from fluid dynamics);

Hence \( n(E) = aE^{-2} \)
Cosmic-ray spectrum

$s = 3$ gives $E^{-2.5}$

$s = 4$ gives $E^{-2}$

Fluxes of Cosmic Rays

(1 particle per $m^2$–second)

Knee
(1 particle per $m^2$–year)

Ankle
(1 particle per km$^2$–year)
Cosmic-ray spectrum

Thermal Maxwell-Boltzmann spectrum

\[ f(v) \propto v^2 e^{-mv^2/2kT} ; \quad f(E) = E e^{-E/kT} \]

One in a million?

Shock or Fermi acceleration
Cosmic-ray spectrum

Thermal Maxwell-Boltzmann spectrum

\[ f(E) = \frac{1}{E} e^{-\frac{mv^2}{2kT}} \]

Acceleration

Only one in a million
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Cosmic-ray Composition

Ordinary thermal matter in sun, stars, interstellar medium
Cosmic-ray Composition

Ordinary thermal matter in sun, stars, interstellar medium

Big hole at Li, Be, B
Smaller hole at sub-iron elements
Cosmic-ray Composition

Blue – thermal matter
Red – cosmic rays
Cosmic-ray Composition

Blue – thermal matter
Red – cosmic rays
Cosmic-ray Composition

Nuclear spallation of cosmic rays

Cosmic ray C,N,O + thermal particles \rightarrow Li, Be, B
Cosmic-ray Composition

Blue – thermal matter
Red – cosmic rays

Relative Abundance (Si=100)

Nuclear Charge Z
Cosmic-ray Composition

Blue – thermal matter
Red – cosmic rays

\[ \approx 5 \text{ g/cm}^2 \]
Cosmic-ray Composition

\[
\frac{5 \text{ g}}{\text{cm}^2} \times \frac{1 \text{ cm}^3}{\text{proton}} \times \frac{1 \text{ proton}}{1,6 \times 10^{-24} \text{ g}} = 3 \times 10^{24} \text{ cm} = 1 \text{ Mpc}
\]

Cosmic rays are extragalactic

30 kpc
Cosmic-ray Composition

\[
\frac{5 \text{ g}}{\text{cm}^2} \times \frac{1 \text{ cm}^3}{\text{proton}} \times \frac{1 \text{ proton}}{1,6 \times 10^{-24} \text{ g}} = 3 \times 10^{24} \text{ cm} = 1 \text{ Mpc}
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Cosmic rays are extragalactic
Cosmic-ray Composition

$\frac{5 \text{ g}}{\text{cm}^2} \times \frac{1 \text{ cm}^3}{\text{proton}} \times \frac{1 \text{ proton}}{1.6 \times 10^{-24} \text{ g}} = 3 \times 10^{24} \text{ cm} = 1 \text{ Mpc}$

Cosmic rays are extragalactic
Cosmic-ray Composition

\[
\frac{5 \text{ g}}{\text{cm}^2} \times \frac{1 \text{ cm}^3}{\text{proton}} \times \frac{1 \text{ proton}}{1,6 \times 10^{-24} \text{ g}} = 3 \times 10^{24} \text{ cm} = 1 \text{ Mpc}
\]

Cosmic rays are extragalactic

Galactic:
Most probably supernova blast wave shocks
Status after 102 years

• Can’t see through mist
Status after 102 years

- Can’t see through mist
- Look at gammas instead (since ~ 1980)
Status after 102 years

- Can’t see through mist
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- Indeed SNRs glow
Status after 102 years

- Can’t see through mist
- Look at gammas instead (since ~ 1980)
- Indeed SNRs glow
- Protons or electrons?
Status after 102 years

• Can’t see through mist

• Look at gammas instead (since ~ 1980)

• Indeed SNRs glow

• Protons or electrons?

• Fermi space telescope 14 Feb. 2013, SNR IC443 – indeed protons!
Status after 102 years

Fluxes of Cosmic Rays

(1 particle per m²-second)

Knee
(1 particle per km²-year)

Ankle

10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20 10^21

Energy (eV)

Galactic (SNRs)  Extragalactic(?)

N

Number of particles
Status after 102 years

- Can’t see through mist
- Look at gammas instead (since ~ 1980)
- Indeed SNRs glow
- Protons or electrons?
- Fermi space telescope 14 Feb. 2013, SNR IC443 – indeed protons!
- Particle and photon astronomy
Why are cosmic rays important?

- Only one in a million of interstellar gas
- But millions of times more energy
Why are cosmic rays important?

• Only one in a million of interstellar gas
• But millions of times more energy
• Thus their speed is c (for energies > $10^9$ eV)
Why are cosmic rays important?

- Only one in a million of interstellar gas
- But millions of times more energy
- Thus their speed is $c$ (for energies $> 10^9$ eV)
- Equipartition of energy: light $\approx$ magnetic field $\approx$ interstellar matter $\approx$ cosmic rays $\approx 1$ eV/cm$^3$
Why are cosmic rays important?

• Only one in a million of interstellar gas

• But millions of times more energy

• Thus their speed is $c$ (for energies $> 10^9$ eV)

• Equipartition of energy: light $\approx$ magnetic field $\approx$ interstellar matter $\approx$ cosmic rays $\approx 1 \text{ eV/cm}^3$

• Cosmic rays are young: $d = 1 \text{ Mpc at } c = 3 \times 10^8 \text{ m/s implies } \sim 10^7 \text{ years}$
Cosmic-ray Composition

How much (little) is 5 g/cm²......?
How much (little) is 5 g cm$^{-2}$?

1 Atmosphere = 100 kPa = $10^5$ N/m$^2$ = $10^4$ kg/m$^2$ = 1000 g/cm$^2$

200 x
Cosmic-ray showers

- Image of cosmic-ray showers above Earth
- Diagram showing particle interactions:
  - E = 10^{15} eV
  - N = 10^6
  - N(e) = 18%
  - N(\gamma) = 18%
  - N(p, n, \pi) = 0.3%
  - N(\mu) = 1.7%

- Depiction of charged particles and gamma rays forming a shower
Topics

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- Helioclimatology
Dark matter
Dark matter
Dark matter
Dark matter
Dark matter

- Neutrinos: 10%
- Photons: 15%
- Atoms: 12%
- Dark Matter: 63%
Dark matter

- > 90% in stars
- < 10% interstellar matter
Dark Energy

- Dark Energy
- Accelerated Expansion
- Afterglow Light Pattern 400,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Inflation
- Quantum Fluctuations
- 1st Stars about 400 million yrs.
- Big Bang Expansion

13.7 billion years
Dark matter-energy

- Dark Energy: 72%
- Dark Matter: 23%
- Atoms: 4.6%

- Dark Matter: 63%
- Photons: 15%
- Neutrinos: 10%
- Atoms: 12%
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Neutrino Astronomy

• Postulated: Pauli 1930

\[ n \rightarrow p^+ + e^- + \nu \]
Neutrino Astronomy

• Postulated: Pauli 1930
  \[ n \rightarrow p^+ + e^- + \nu \]
• Detected: 20 July 1956

Frederick Reines
& Clyde Cowan
Neutrino Astronomy

Neutrino event in LHC, CERN
Neutrino Astronomy

• Postulated: Pauli 1930
  \[ n \rightarrow p^+ + e^- + \nu \]

• Detected: 20 July 1956

• In nature: August 1965 (ERPM, Boksburg)

Frederick Reines & Clyde Cowan

Friedel Sellschop (WITS)
Neutrino Astronomy

• Postulated: Pauli 1930
  \[ n \rightarrow p^+ + e^- + \nu \]
• Detected: 20 July 1956
• In nature: August 1965 (ERPM, Boksburg)
• Astrophysical importance: non-interacting
Neutrino Astronomy

FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.
Neutrino Astronomy

- Postulated: Pauli 1930
  \[ n \rightarrow p^+ + e^- + \nu \]
- Detected: 20 July 1956
- In nature: August 1965 (ERPM, Boksburg)
- Astrophysical importance: non-interacting

Neutrinos → muons → Cherenkov light
electrons
tauons
Neutrino Astronomy

• Postulated: Pauli 1930
  \[ n \rightarrow p^+ + e^- + \nu \]
• Detected: 20 July 1956
• In nature: August 1965 (ERPM, Boksburg)
• From sun: Homestake, since 1970
  ----- 6.5×10^{10} per cm^2 per second
Neutrino Astronomy

• Postulated: Pauli 1930
  \[ n \rightarrow p^+ + e^- + \nu \]
• Detected: 20 July 1956
• In nature: August 1965 (ERPM, Boksburg)
• Astrophysical importance: non-interacting
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Neutrino Astronomy

• Postulated: Pauli 1930
\[ n \to p^+ + e^- + \nu \]
• Detected: 20 July 1956
• In nature: August 1965 (ERPM, Boksburg)
• Astrophysical importance: non-interacting
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• Supernova 1987A: 24(!) neutrinos seen
Neutrino Astronomy

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- Supernova 1987A: 24(!) neutrinos seen
- IceCube
Neutrino Astronomy – Ice Cube
Neutrino Astronomy – Ice Cube

IceCube Lab

IceTop
81 Stations
324 optical sensor

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

DeepCore
8 strings-spacing optimized for lower energies
480 optical sensor

Eiffel Tower
324 m

Bedrock
Neutrino Astronomy – Ice Cube

SKA = 1 km$^2$; $R \approx 3 \times 10^9$

IceCube = 1 km$^3$; $R \approx 2.6 \times 10^9$
Neutrino Astronomy – Ice Cube

IceCube Lab

IceTop
81 Stations
324 optical sensor

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

DeepCore
8 strings-spacing optimized for lower energies
480 optical sensor

Look down
• Postulated: Pauli 1930
\[ n \rightarrow p^+ + e^- + \nu \]
• Detected: 20 July 1956
• In nature: August 1965 (ERPM, Boksburg)
• From sun: Homestake, since 1970
• Supernova 1987A: 24(!) neutrinos seen
• Bert and Ernie: 15 May 2013
\[ > 10^{15} \text{ eV} \]
Neutrino Astronomy

• Postulated: Pauli 1930
  \[ n \rightarrow p^+ + e^- + \nu \]
• Detected: 20 July 1956
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• From sun: Homestake, since 1970
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  \[ > 10^{15} \text{ eV} \]
Particle Astrophysics

Astroparticle Physics
• South African astronomy
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• Cosmic-ray variations
• “Cosmic” rays from the sun
• Helioclimatology
Cosmic ray spectrum

Fluxes of Cosmic Rays

Number of particles vs. Energy (eV)

- Knee: 1 particle per m²-year
- Ankle: 1 particle per km²-year

(1 particle per m²-second)
Cosmic-ray counts

Cosmic rays: Hermanus neutron monitor

Counts (=100 in March 1987)

Year


110 100 90 80 70

11 years
The Sun
Sunspots
Sunspots
Sunspots since 1818

19 cycles of 11 years each
Solar wind and Coronal Mass Ejection
The Solar Wind and Heliosphere

- $V_{\text{wind}} \sim 400 \text{ km/s}$
- $V_{\text{sound}} \sim 40 \text{ km/s}$
- ~150 Astronomical Units (AU)

- Standing shock
- Earth
- Bow Shock
- Heliosphere
- Terminaton Shock
- Standing shock
- Sun
Cosmic rays in the heliosphere

Solar wind 400 km/s

and magnetic field

Heliosphere
Cosmic rays in the heliosphere

Solar wind 400 km/s and magnetic field
Cosmic ray spectrum

Fluxes of Cosmic Rays

- Knee: 1 particle per m²-year
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Number of particles vs. Energy (eV)
Cosmic ray spectrum

Energy (eV)

Number of particles

Fluxes of Cosmic Rays

Knee
(1 particle per m²-year)

Ankle
(1 particle per km²-year)

(1 particle per m²-second)
Cosmic rays and sunspots

11 years

Hermanus neutron monitor

Sunspots
The Voyager Mission – launched 1977

Voyager 1
130 AU

Voyager 2
The Voyager Mission

265 MeV/n He Voyager 1 Counts

Solar min ~1 %/AU

Solar max ~2 %/AU

[Graph showing data points and markers for 1977, 1987, 1998, and 2009?]
The Voyager Mission

25 August 2012

100 years (plus 18 days) after 7 August 1912
Humanity's farthest journey

Voyager 1
130 AU

Voyager 2

Sun

Bow Shock • • Heliosphere

Heliosheath
Three forms of the Transport Equation

$$\frac{\partial U}{\partial t} + \nabla \cdot (VU - K \cdot \nabla U) - \frac{1}{3} (\nabla \cdot V) \frac{\partial}{\partial p} (pU) = 0$$

or, in terms of $f$

$$\frac{\partial f}{\partial t} + \nabla \cdot (Vf - K \cdot \nabla f) - \frac{1}{3p^2} (\nabla \cdot V) \frac{\partial}{\partial p} (p^3 f) = 0$$

or, slightly manipulated

$$\frac{\partial f}{\partial t} + V \cdot \nabla f - \nabla \cdot (K \cdot \nabla f) - \frac{1}{3p^2} (\nabla \cdot V) \frac{\partial f}{\partial \ln p} = 0$$

Too difficult to solve analytically …..
Cosmic-ray diffusion tensor

$$K = \begin{pmatrix}
\kappa_\parallel & 0 & 0 \\
0 & \kappa_\perp & \kappa_T \\
0 & -\kappa_T & \kappa_\perp
\end{pmatrix}$$

each \( \kappa_i = \kappa_i(r, P, t) \)

- How do the solar wind and the heliopsheric magnetic field have to look to explain the observed cosmic-ray intensity variations?
- Does this agree with what we observe of the solar wind and heliospheric magnetic field?
Experimental work

Cosmic rays: Hermanus neutron monitor

Counts (=100 in March 1987)

Year

11 years
Experimental work

Cosmic rays: Hermanus neutron monitor

11 years

Counts (≡100 in March 1987)

1 June 1957

Year
Sanae
Sanae Neutron Monitor

2 m
30 tons
Neutron monitors – sensitive to the neutrons
Neutron monitor network
The poles are better

Cutoff Rigidity
15 GV

Cutoff Rigidity
0 GV
The poles are better

A window into geospace

Cutoff Rigidity
15 GV

Cutoff Rigidity
0 GV
Mini neutron monitors
Mini neutron monitors
Mini neutron monitors

French/Italian Station Dome C

3200 m (15 x sea level)
Mini neutron monitors

Sierra Negra, Mexico, 4200 m
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Solar flare and coronal mass ejection - shocks
Ground-level Enhancement (GLE) = "cosmic" rays from sun
Ground-level Enhancement (GLE) = "cosmic" rays from sun

71 times since 1942
Ground-level Enhancement (GLE) = "cosmic" rays from sun

See:
- Particles (GLE)
- Flare and CME (3D-stereo)
- Shock (3D-stereo)
- Gammas
- X-rays
- Radio
- Magnetic fields
- Kinks
GLE 42 on 29 September 1989

% Increase

Time (hr:min)
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Climate change

Fig. 2: $CO_2$ and $CH_4$ over the last 1,000 years$^{(1-4)}$
Climate change

Reconstructed Temperature

Medieval Warm Period

Temperature Anomaly (°C)

Little Ice Age

2004
Climate change

Fig. 2: $CO_2$ and $CH_4$ over the last 1,000 years

The Hockey Stick Graph
Climate change

Fig. 2: \( CO_2 \) and \( CH_4 \) over the last 1,000 years\(^{(1-4)} \)

The Hockey Stick Graph

International Panel on Climate Change (IPCC)
Climate change

400 Years of Sunspot Observations

Sunspot Number

1600 1650 1700 1750 1800 1850 1900 1950 2000

Maunder Minimum
Dalton Minimum
Modern Maximum
History of the Sun

Solar observables

Be 10 & C 14
Aurorae (undefined beginning)
Sunspots (quantitative 1610)
Corona at eclipse 1715
Geomagnetic data 1818
Disk photography 1857
Solar flares 1859
Solar constant 1890
Spectrograms 1915
Cosmic rays ~ 1920
Coronagraph 1940
Radio 1945
X-rays 1949
Magnetograms 1953
Solar wind 1962
Gamma rays 1962
Heliospheric magnetic field 1966
Neutrinos 1967
Coronal mass ejections 1971
Helioseismology 1980

Updated from Eddy (1976)

1300 1400 1500 1600 1700 1800 1900 2000
History of the Sun

Solar observables

- Be 10 & C 14
- Aurorae (undefined beginning)
- Sunspots (quantitative 1610)
- Corona at eclipse 1715
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- Solar wind 1962
- Gamma rays 1962
- Heliospheric magnetic field 1966
- Neutrinos 1967
- Coronal mass ejections 1971
- Helioseismology 1980

Updated from Eddy (1976)

1300 1400 1500 1600 1700 1800 1900 2000
Paleo-cosmic rays: $^{14}\text{C}$ and $^{10}\text{Be}$
Paleo-cosmic rays: $^{10}\text{Be}$
$^{10}$Be in polar ice ... Earth's neutron monitor

Steinhalber et al. (2012)
$^{10}\text{Be}$ in polar ice ... Earth's neutron monitor

Steinhalber et al. (2012)
Paleo-cosmic rays: $^{10}\text{Be}$
Ice shelf in Queen Maud Land
Ice shelf in Queen Maud Land
Ice shelf in Queen Maud Land

23 annual layers
Shallow drilling ....... ~ 60 years deep
Pilot Project 2006
Pilot project 2006

$^{10}\text{Be}$ and Cosmic Rays

Cosmic Ray Intensity (Sanae)

$^{10}\text{Be}$ in $10^4$ atoms per gram
Shallow drilling ....... ~ 60 years deep
• Particle Astronomy after 102 years:
  25 August 2012 – longest journey ever completed
  14 February 2013 – SNRs *do* produce CR protons
  15 May 2013 – two true cosmological neutrinos seen
South African Astronomy

- Radio Astronomy
- Optical Astronomy
- Gamma-ray Astronomy
- Particle Astronomy after 102 years:
  - 25 August 2012 – longest journey ever completed
  - 14 February 2013 – SNRs *do* produce CR protons
  - 15 May 2013 – two true cosmological neutrinos seen
• Pieter Stoker, Helena Krüger, Anne Mans, Gert Benadé & Students & Antarctic expedition members

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• NASA/Wikipedia