Variations of Solar and Cosmic Ray Cycles at the Maunder Minimum

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What $^{14}\text{C}$ and $^{10}\text{Be}$ tell about the Maunder Minimum

Cosmic ray variations
Solar Cycle length
Magnetic polarity reversal
Heliospheric current sheet
Precursory features

Any similarity to the last solar cycle minimum?
Any information on rotation?
Any impact on climate?
$^{14}$C and $^{10}$Be: Proxy of past cosmic ray variations

**Galactic cosmic rays**

Air shower in the atmosphere

\[ ^{14}N + n \rightarrow ^{14}C + p \]

$^{10}$Be

Antarctic/Greenland Ice

Tree ring

Carbon-14 and Boron-10: Proxy of past cosmic ray variations

Neutron Flux at Climax

Sunspot number

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

Year AD


0 50 100 150 200 250 300 350 400

Cosmic rays

Sunspot number

Clear signal

Dating errors of a few years

Distorted signals

Absolute age
Changes in the solar cycle lengths

Carbon-14: (Cosmogenic nuclide)

Actual mean length over the shaded period (+/-1yrs)

~9 yrs  ~10.5 yrs  ~12 yrs  ~13.5 yrs  ~14 yrs

~11 yrs  ~10 yrs  ~13 yrs

10-11 yrs

$\Delta^{14}C$ (permil)

$^{14}C$ in annual tree rings

Dacadal: Stuiver et al., 1998

Annual:
Onset of the Maunder Minimum

**Maunder Minimum (1645-1715 AD)**

- **Frequency (1/yr)**

  - 11 yrs
  - 14 yrs

**Vaquero et al., 2011**

Both suggest gradual onset

- Two 12-13 year cycles before the onset

**Miyahara et al., 2010**

- ~9 yrs
- ~27 yrs for two cycles

**Vaquero et al., 2011**

Fig 1. Wavelet spectrum of carbon-14
Onset of the Spoerer Minimum

(a) 14C content in tree rings (Miyahara et al., 2010)

(b) Wavelet Spectrum of 14C

13-ys

(c) Band pass filtered 14C

dotted: 1-25yrs
solid: 10-25yrs

Two 13yr cycles before the onset
Two lengthened cycles before the onset of the Maunder Minimum

First lengthened cycle
> weaker polar field

Second lengthened cycle
> both weakened polar field
> & slower meridional circulation

~9 yrs ~27 yrs for two cycles

Vaquero et al., 2011
Cosmic ray variation at the Maunder Minimum

Miyahara et al., IAU proc., 2009,
Yamaguchi et al., PNAS, 2010

Tree ring:
No dating error

Ice core:
a few years of dating errors

- 1-year scale enhancements
- 30-50% higher at negative polarity
Cosmic ray variation & Solar magnetic polarity

1. Magnetic polarity

2. Tilt angle

Jokipii & Kota 2007
Variable “22-year” pattern of cosmic rays

1. Solar polarity

If 5-75 degrees (modern)

If 30-75 degrees

If 0-75 degrees

2. Tilt angle

Miyahara et al., 2009

Kota & Jokipii, 2003
Flattened current sheet and cosmic-ray spikes

Based on Kota & Jokipii, 1983; 2003

Miyahara et al., 2009

Tilt angle: 0 degree

Tilt angle: ~5 degree

“Flattened current sheet model” reproduces the pattern of 10Be variation, but needs additional impact from weakened solar wind
Any similarity to the last solar cycle minimum?

Closer to AD1954.... than AD2009....

Cliver, Svalgaard, Ling, 2004
Rotation rate at the Maunder Minimum (equatorial)

Modern:
26.24 days (Synodical) (Sidereal : 24.47 days)

Maunder Minimum:
25.3~26.1 days (@1642-1644, Eddy1976)
27 days (@1642-1644, Abarbanell1980)
27.5 days (@1684+1686, Ribes1993)
27.5 days (@1684, Sidereal:25.5 days, Flamsteed1684)
28.5±0.5 days (@1684, Vaquero2002)
Historical records of lightening

Modern
• 26.7 day solar rotational period (Muraki+2004; Sato+2005)
  (GCR / solar wind / UV …)

Weather records around the Maunder Minimum
Myou-hou-in Nikki (diary)
AD1695-1786
AD1695-1766
Mujou-hou-in Nikki (diary)
AD1668-1694

Reflecting the altitude of active region??
Lightening “27-day” cycle (very preliminary)

Maunder Minimum (cycle minima)

If the altitude of Active region is known
> Estimation of rotation rate at known latitude

If not known, solar cycle variation of active regions (larger variation)
Possible pathways for solar influence on climate change

Most unknown part

10Be flux

Year AD
Response of climate to cosmic-ray spikes at the Maunder Minimum

Yamaguchi, Yokoyama, Miyahara et al., PNAS, 2010
Superposition of four 1-year spikes for $^{14}$C (GCR) and $^{18}$O (climate)

No time lag!

Yamaguchi, Yokoyama, Miyahara et al., PNAS, 2010
Summary:
What $^{14}$C and $^{10}$Be suggests for the Maunder Minimum

Solar Cycle length : $\sim$14 years
Magnetic polarity reversal : YES ($\sim$28-year period)
Onset : Two preceding 12-13 year cycles
Cosmic ray variations : Strong 28-year component
Heliospheric current sheet : More flattened
Any impact on climate? : YES! (possibly through GCR)
Any similarity to the last solar cycle minimum? :
More extreme situation at the Maunder Minimum
Any information on rotation?
Lightening data as well as sunspot record may help
Possible influence of solar rotation on clouds

Takahashi et al., ACP, 2010
Hong, Miyahara et al., JASTP, 2011

Amplitude for 25-30 day period

/quote

Outgoing Longwave Radiation = high clouds analyzed for each 10 x 10 degree grid
Solar rotational signals are detected around the tropics (only at solar cycle maxima)
Comparison between cosmic rays, solar radio flux with OLR

F10.7 radio flux (red) vs OLR

Cosmic rays (inverted, blue) vs OLR

High-pass filtered (bandwidth: 80 days)
Red: Solar flares (Coronal Mass Ejections (CMEs))
Black: Current sheet passage

Forbush Decrease

Heliospheric current sheet

(Solar Max)
AD 2000 (solar max)

Correlation coefficient

Lags (days)

Response to GCRs is local, but localized to the areas that can control Hadley cell, monsoonal activity, and cyclone activity etc.
Comparison between cosmic rays, solar radio flux with OLR

Cosmic rays (inverted, blue) vs OLR

F10.7 radio flux (red) vs OLR

Day of Year 2000

High-pass filtered (bandwidth: 80 days)
Solar differential rotation

Differential Rotation

Butterfly diagram

Red: F10.7 solar radio flux
Blue: galactic cosmic rays

Heliospheric current sheet
AD 2000 (solar max)

Correlation coefficient

Lags (days)

Cosmic rays (blue) vs MODIS

High (<440 mb)

Middle (inverted)

Low (>680 mb)

inverted

@Equatorial summer

Cosmic ray flux ↑

OLR (equatorial region) ↓

High-altitude clouds ↑
Influence of QBO on 27-day signal in OLR?

Hong, Miyahara et al., JASTP, 2011

Large 27-day variability at the 11-year solar cycle maxima

> Separation of the duration by
  - Solar Max/Min
  - QBO phases
Influence of QBO on tropospheric cloud?

Hong, Miyahara et al., JASTP, 2011

> QBO influence on tropospheric cloud activity

➢ Stronger Stratosphere-Troposphere interaction at solar max? (which might contribute to 2-9yr short-term climate variability)
Important parameters for the pattern of cosmic-ray variation
1. Solar polarity
2. Tilt angle of heliospheric current sheet
SOHO/MDI

**Active**

- **Sunspots**
- **Solar magnetic field**
  - Complex magnetic field
  - Red: +  Blue: —
  - Tilt angle: ~75 degrees
  - ~400 km/s

**Inactive**

- **Sunspots**
- **Solar magnetic field**
  - Dipole magnetic field
  - Tilt angle: ~5 degrees
  - ~400 km/s

**Heliospheric magnetic field**

- **Tilt angle**: ~75 degrees

11-years
Solar modulation of Galactic Cosmic Rays (GCRs)

- Charged particles (mainly protons)
- Accelerated at supernova remnant

@ ~ edge of the heliosphere

@Earth

- diffusion
- advection by solar wind
- drift

Webber & Higbie 2010
Reconstructed solar decadal cycles in the past

Carbon-14: (Cosmogenic nuclide)

Sunspot Number
- SN ($^{14}$C)
- SN ($^{10}$Be-pol)
- SN ($^{10}$Be-global)

Actual mean length over the shaded period

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Dacadal: Stuiver et al., 1998

Carbon-14 in annual tree rings