The connection between cosmic rays, clouds and climate

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The connection between cosmic rays, clouds and climate

1. The cosmoclimatological hypothesis
   – Origin of cosmic rays
   – Linking cosmic rays to climate
   – Presentation of the hypothesis

2. The final piece of the puzzle
   – The microphysical mechanism, theoretically and experimentally
   – How relevant is cosmic rays for climate in the real atmosphere?

3. Conclusion
Cosmic Rays

Super Nova Remnant
Acceleration of cosmic rays

Solar magnetic field

Solar system
Cosmic rays in the atmosphere

Incoming proton of 100 GeV

20 km

0 km

Ionizes the atmosphere

Produces new cosmogenic isotopes, e.g. $^{14}$C, $^{26}$Al, $^{10}$Be

ICE
Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago

The formation of stalagmites in northern Oman has recorded past northward shifts of the intertropical convergence zone\(^3\), whose northward migration stops near the southern shoreline of Arabia in the present climate.

U. Neff et al., Nature 411, 290 - 293 (2001)
How can STARS influence Climate?

Net effect of clouds is to cool the Earth by about 30 W/m$^2$
Link between Low Cloud Cover and Galactic Cosmic Rays?

Solar cycle variation

ISCCP IR Low cloud data

Calibration?

Empirical evidence for a relation between cosmic rays and climate

If the link is between cosmic rays and clouds, what would the mechanism be?
Precursor to clouds: Aerosols

Cosmic Ray Ionization

1-2 nm stable aerosols

Growth

Cloud Condensation Nuclei > 50 nm
Aerosols and microphysics of clouds

Satellite observations of ship tracks

Visible: 0.9 mm
Experimental challenges

2004 - 2007

H$_2$SO$_4$ concentration $\sim 2 \times 10^8$ (cm$^{-3}$)

O$_3$ $\sim$ 25 ppb

SO$_2$ $\sim$ 300 ppt

RH $\sim$ 35%

1-2 nm stable aerosols

So experimentally there is good evidence for the generation of ultrafine aerosols by ions ~ 1-3 nm

• An important remaining question:
Will the small aerosols grow to Cloud Condensation Nuclei (~ 50 nm)?

Nucleation

If not no impact on clouds.

• CCN
RESULTS FROM GEO-CHEM-TOMAS Global Circulation Model
(No ion-effects on growth)

Solar cycle response

Data from: Snow-Kropla et al. 2011
Modeling says NO to an effect of ions on CCN
Is the theory dead again?

IN THE CLOUDS —
Sun-clouds-climate connection takes a beating from CERN

Cosmic rays and other radiation may help clouds form, but their effect is marginal.

JOHN TIMMER - 10/28/2016, 3:28 PM
Cosmic ray theory

1996 - 2016

Sorry for the trouble
More particles competing for the same gas, therefore slower growth and larger losses, as also seen in model results.

Svensmark, Enghoff, Pepke Pedersen
Addition of aerosols using ionization

Contradicts the model results

Svensmark, Enghoff, Pepke Pedersen
Coronal Mass Ejections

Natural experiments for testing the GCR-atmosphere link
AERONET, SSM/I, MODIS and ISCCP data for 5 strongest Forbush decreases

AERONET  

SSM/I  
Svensmark, Enghoff, Shaviv, Svensmark, J. Geophys Res., 2016
Experiments and observations suggest that aerosols grow to Cloud Condensation Nuclei (CCN) > 50 nm. Will cosmic rays help the growth? What mechanism is responsible?

1-2 nm stable aerosols

GROWTH?
Mainly from $\text{H}_2\text{SO}_4$–$\text{H}_2\text{O}$ gas
Cosmic Rays

Ions

Aerosol

$M_{aerosol} + m_{ion}$

Ions   Aerosols

$m_{ion} \rightarrow M_{aerosol} \rightarrow M_{aerosol} + m_{ion}$

A so far ignored effect
A few numbers

Growth from neutral molecules

\[ \text{H}_2\text{SO}_4-\text{H}_2\text{O} \sim n_0 \sim 10^6 \text{molecules/cm}^3 \]

Growth from ions

Ions \sim 10^3 \text{ions/cm}^3

Naively:

\[ \text{GR}_{\text{ion}}/\text{GR}_0 \sim n_{\text{ion}}/n_0 \sim 10^{-3} \sim 0.1\% \]

Enhanced interactions

1. Coulomb forces
2. Mirror forces
3. Van der Waals forces
4. Viscous forces
After 3100 Hours of measurements we get:

\[ \Delta q = 45 \text{ ion-pairs cm}^{-3} \text{s}^{-1} \]
\[ \Delta q = 186 \text{ ion-pairs cm}^{-3} \text{s}^{-1} \]

Theory and experiments are consistent!

Svensmark, Enghoff, Shaviv & Svensmark, Nature Communications 2017 DOI: 10.1038/s41467-017-02082-2
Summery of influence of cosmic rays on clouds

Important: The cosmic ray effect on growth is independent on how small particles are made.
OCEAN

Atmospheric Relevance

HADLEY CIRCULATION

Equator

40 South

40 North

ITCZ
Convergent zone

$\tilde{n}_{\text{H}_2\text{SO}_4} \sim 1 - 3 \times 10^6 \text{ cm}^{-3}$

Time of growth 5-7 days

Supernova Remnant

GCR

Solar Wind

GCR

Solar Wind

Supernova
Remnant

H2SO4

n

Time of growth 5-7 days

OCEAN
Summary

1. Cosmic rays assist the nucleation of small aerosols (1-1.5 nm)
2. Growth of aerosols to CCN assisted by cosmic ray ionization (Microphysical mechanism identified)
3. Explain results on Forbush decreases which result in variations in aerosols and clouds
4. Consistent with climate changes over the Holocene (last 10,000 years) 1-2 °C
5. Consistent with climate change over geological time scales 5-10 °C, e.g. last 500 million years. **Note that these variations are independent of solar variability.**
Climate and our galactic environment
Carbon 13 and super nova activity

\[ \frac{SN(t)}{SN(0)} \]

\[ \delta^{13}C \text{ [per mill]} \]

Time [Myr]

Conclusion

• The ions produced of cosmic rays, help the formation clusters to form and become stable against evaporation. This process is called nucleation and results in small clusters (aerosols).

• The second role of ions is that they accelerate the growth of small aerosols into cloud condensation nuclei – seeds on which liquid water droplets form to make clouds. The more ions the more aerosols become cloud condensation nuclei.

IMPLICATIONS

• When the Sun is lazy, magnetically speaking, there are more cosmic rays and more low clouds, and the world is cooler. When the Sun is active fewer cosmic rays reach the Earth and, with fewer low clouds, the world warms up.

• Cooling’s and warmings of around 2 °C have occurred repeatedly over the past 10,000 years, as the Sun’s activity and the cosmic ray influx have varied.

• Over many millions of years, much larger variations of up to 10° C occur as the Sun and Earth, travelling through the Galaxy, visit regions with more or fewer exploding stars.
Cosmic rays from Meteorites

Titanium 44 (Half-time 63 years)

Stone meteorite

Taricco et al. 2006

Eleanna Asvestari Ilya G. Usoskin Gennady A. Kovaltsov Mathew J. OwensNatalie A. Krivova Sara Rubinetti Carla Taricco

Quantifying the Solar impact:

[Graph showing the relationship between Sea Level Change Rate and Solar Constant over the years with additional images of the Sun.]

Shaviv 2008
Quantifying Solar Forcing over 11 years

Shaviv, 2008

Require an amplification mechanism

CLOUDS
Climate and our galactic environment
pt. 2
Cosmic rays and climate over the last 10,000 years

Bond et al, Science 294, 2001

- Little Ice Age is merely the most recent of a dozen such events during the last 10,000 years

According to icecores, CO₂ levels has been constant ~280 ppm

Last 1000 years
Little Ice Age

Adapted from Kirkby
G in theory
change in % of effective growth velocity

Important for the survivability of aerosols

$[\text{H}_2\text{SO}_4] \sim 10^6 \text{ molecules/cm}^3$
Even the details in the theory fits the experiment