# The connection between cosmic rays, clouds and climate



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# The connection between cosmic rays, clouds and climate

### **1.** The Cosmoclimatological Hypothesis

- Cosmic rays
- Presentation of the hypothesis
- The microphysical mechanism, theoretically and experimentally
- 2. Starformation and Supernova
  - Influence on life

### Cosmic Rays

Super Nova Remnant Acceleration of cosmic rays

Solar magnetic field

Solar system



### Temperatures over the last 1000 years



### How can supernovae influence Climate?

2019-11-01 00:00:00 UTC

www.digital-typhoon.org

Himawari-8 [RGB]

NII/NICT

Net effect of clouds is to cool the Earth by about  $20-30 \text{ W/m}^2$ 



Svensmark & Friis-Christensen, JASTP 1997, Svensmark, PRL 1998, Marsh & Svensmark, PRL, 2000. (update 2005)



### Aerosols and microphysics of clouds Satellite observations of ship tracks





### More than ten years of experimental work

CERN

DTU, National Space Institute



#### ASTRID accelerator, Aarhus Universitet



#### BOULBY Underground Laboratory (1.1 km underground)



### **Experimental challenges**



1-2 nm stable aerosols

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

CCN

 An important remaining question:
Will the small aerosols grow to Cloud Condensation Nuclei (~ 50 nm) ?
Nucleation
If not no impact on clouds.

### RESULTS FROM Global Circulation Models (2009 – present) (No ion-effects on growth)



### Is the theory dead again?



## **Cosmic ray theory**

## 1996 - 2016

Sorry for the trouble

### **Coronal Mass Ejections**

Natural experiments for testing the GCR-atmosphere link



### AERONET, SSM/I, MODIS and ISCCP data for 5 strongest Forbush decreases



Svensmark, Bondo, Svensmark, Geo. Phys. Lett., 2009 Svensmark, Enghoff, Shaviv, Svensmark, J. Geophys Res., 2016

### <u>CERES instrument: The effect</u> on the energy balance



Svensmark, H., Svensmark, J., Enghoff, M.B., Shaviv, J. N., *Sci Rep* **11**, 19668 (2021)

### **<u>CERES instrument:</u>** The effect on the energy balance

### Shortwave



After cosmic ray change (One week average)



Svensmark, H., Svensmark, J., Enghoff, M.B., Shaviv, J. N., *Sci Rep* **11**, 19668 (2021)

Experiments and observations suggest that aerosols grow to Cloud Condensation Nuclei







NGC 2516, 150 million old

Pleiades 200 myr old ~ 1000 stars Distance from solar system ~150 pc





### SN activity and glaciations during the last 500 Myr



Proxy temperature and supernova activity during 200 Myr



Svensmark, Mon. Not. R. Astron. Soc., 423, 1234-1253 (2012)



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### Sedimentary mountains (Grand Canyon)



One can estimate the fraction of organic material buried as sediments

## Organic burial in sediments and supernova activity



### Galactic cosmic rays and burial of organic matter during the history of Earth



#### Galactic cosmic rays and burial of organic matter The source of oxygen Proterozoic Archean Phanerozoic 2.0 WHY 1.5 GCR(t)/GCR(0) Galactic cosmic rays and the source of oxygen 1.0 0.5 Oxygen 0.0 - I - - --3500 -3000 -2500 -2000 -1500 -1000 -500 0 **Photosynthesis** Time [Ma] Proterozoic Phanerozoic Archean $6CO_2 + 6H_2O \leftrightarrow C_6H_{12}O_6(glucose) + 6O_2$ 0.30 0.25 0.20 Burial of organic 0.15 matter in sediments 0.10 0.05 0.00Supernovae have helped the production of oxygen. -3500 -3000 -2500 -2000 -1500 -1000 -500 0 Oxygen is needed for the evolution of complex life

Age [Ma]

### Sagittarius dwarf galaxy



Tomás Ruiz-Lara et al. "The recurrent impact of the Sagittarius dwarf on the Milky Way star formation history", Nature Astronomy, 2020

Gaia Data Release 2 (DR2) data

### Conclusions

Variations in cosmic rays are associated with changes in Earth's climate. Strong empirical evidence on all time scales

**Evidence suggests that clouds link to cosmic ray variations** 

- Solar activity affects the climate (days to 10.000 years)
- Supernova activity affects climate (million of years)
- Burial of organic matter follows variations in supernovae history. Which is the source of oxygen and therefore fundamental for the evolution of complex life