A proton's way from the Sun to Umeå

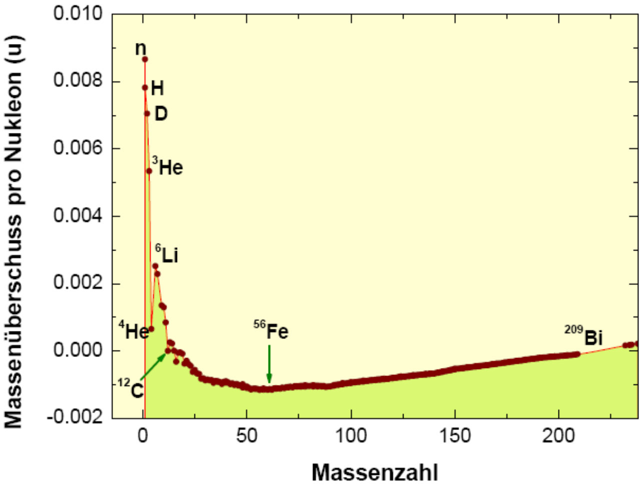
Boris Lemmer

22th of October 2007

Let’s follow the journey of a solar proton!

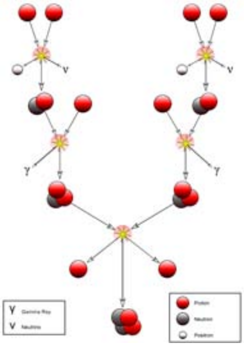
Let us start from the beginning:
Where do they come from?
$\rightarrow$ fusion reaction in the core of the Sun
Two main processes, converting mass into energy due to Einstein’s $E = mc^2$

Fusion and fission: Why and when?



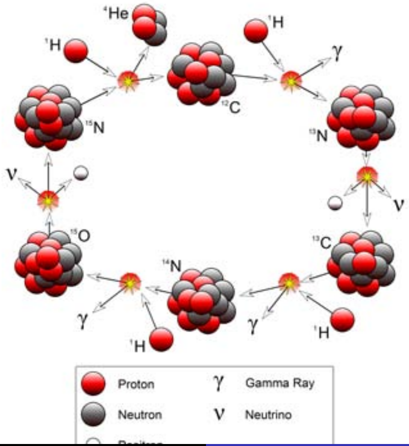
Proton-proton chain reaction

- Most important reaction for stars like the Sun or smaller
- Hydrogen is converted into Helium



CNO Cycle

Important for bigger stars, but quite uninteresting for our Sun (only 1.6 % of its energy generation)

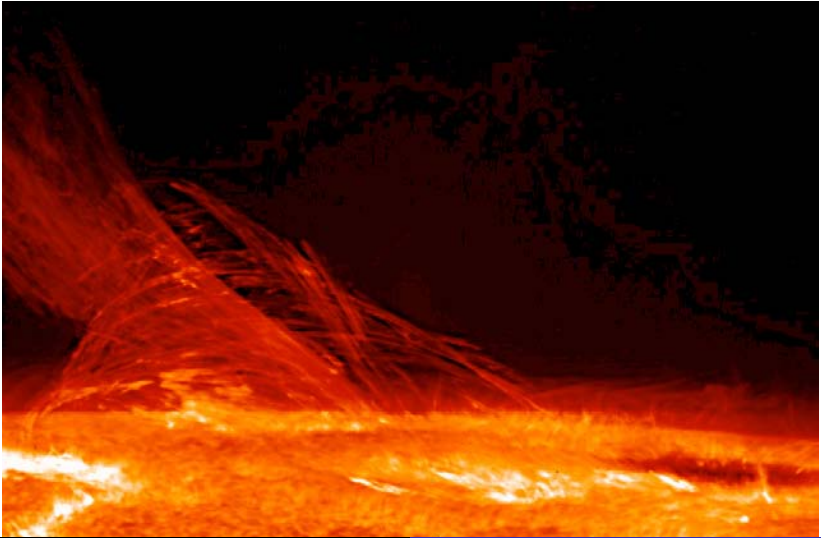


Floating with the solar wind

Protons leave the Sun constantly (mass reduction: $10^9 \frac{kg}{s}$). The way varies:

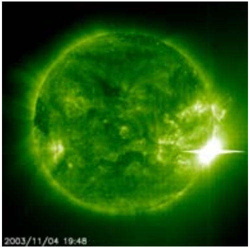
- **Slow solar wind** (closed field lines, 250-400 $\frac{\mathrm{km}}{\mathrm{s}} \doteq 1keV$, $11 \frac{\mathrm{particles}}{\mathrm{cm}^3}$)
- **Fast solar wind** (open field lines, 400-800 $\frac{\mathrm{km}}{\mathrm{s}} \doteq 3keV$, $3 \frac{\mathrm{particles}}{\mathrm{cm}^3}$)
- **Special events** (Coronal mass ejections, solar flares (up to MeV range!))

Solar flares

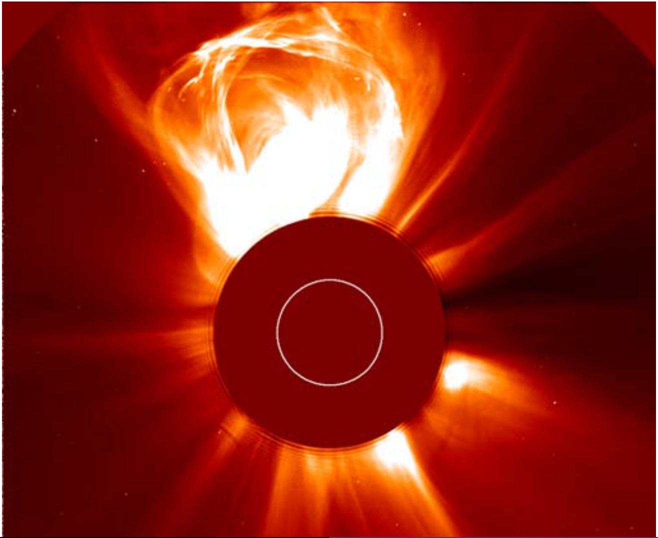


Solar flares

- Violate explosions, found in the area of Sunspots
- Energy of over 10^{20} J is released (billion megatons of TNT)
- Bright flash of X-rays named them 'flare'



Coronal mass ejections



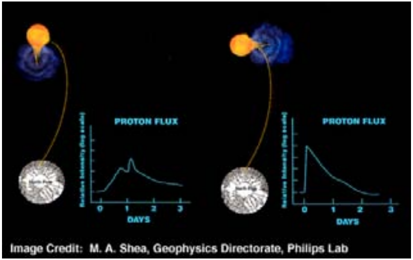
Coronal mass ejections

- Large amount of ejected particles ($\approx 10^{12}$ kg, primarily protons)
- 1-6 CMEs per day, depending on phase of solar circle
- Unclear: Dependency between solar flare and CME.

Idea: flare drives CME
Problem: Only 60% of flares connected with CMEs. Sometimes CMEs start earlier then flares.

The great proton storm of 20.01.2005

- Solar and Heliospheric Observatory (SOHO) observed proton storm with 100 MeV peak
- Four powerful flares from sunspot NOAA720 were followed my giant final flare
- Straight connection from spot to earth. Acceleration process still not completely understood.



Where are the protons going?

- Most of them are just kicked into outer space
- If directed to earth, could they hit an astronaut?
- What will happen when they reach the earth?

A proton flux is dangerous radiation!

- Electromagnetic interaction with matter can cause light emission (by excitation of atoms) and ionization
- Ionization can change the structure of complex molecules
- Amount of potential damage must be described and measured

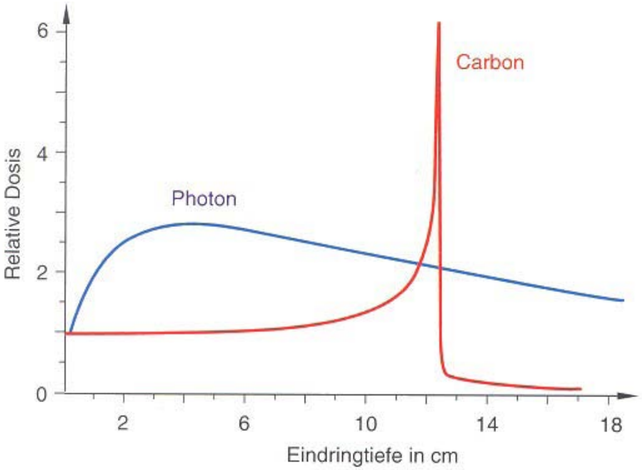
The Bethe-Bloch formula

Effective description of energy deposition in matter by the Bethe-Bloch formula:

$$-\frac{dE}{dx} = D\rho Z^2 \frac{Z_A}{A_A} \frac{1}{\beta^2} \left[\ln \left\{ \frac{2m_e c^2 \beta^2 \gamma^2}{I} - \beta^2 \right\} \right] \frac{\mathrm{MeV}}{\mathrm{m}}$$

$D = 0.0307 \mathrm{MeV} \frac{\mathrm{m}^2}{\mathrm{kg}} / \rho$: dense of matter
Z_A, A_A : charge and mass number of absorber
Z : particle charge/m_e : electron mass
Integration guides us to the penetration depth.
Protons with low energies can be absorbed by a sheet of paper, but high energy particles have to be shielded seriously (100 MeV protons penetrate 11cm of water!).

Protons have high ionization density!



Damage in a cell

Useful units in radiation classification:

- *Absorption dose*: 1 Gray ($1Gy = 1\frac{J}{kg}$)
- Additional information about kind of damage considered by the *absorption dose*:
  1 Sievert ($1Sv = factor \cdot 1Gy$)
  The '*factor*' varies between 1 (electrons) and 20 (neutrons with special energy)
- Also used: *effective dose*. Considers also the type of organs being damaged.

Problems for our astronaut

- Ionized atoms can create new compounds like the toxic H_2O_2
- DNA in the cell core might get damaged
- Cell can either die or (worse!) mutate

Radiation Sickness

This is how you suffer from radiation:

- **200 mSv** Change of blood count
- **0,2-1 Sv** Vomiting, low blood counts, temporary male sterility
- **1-2 Sv** 10% fatality after 30 days
- **2-3 Sv** 35% fatality, loss of hair all over the body
- **3-4 Sv** 50% fatality, uncontrollable bleeding
- **more than 6 Sv** intense medical care needed immediately (bone marrow transplant)

All values for acute exposure!
Average exposure: 4 mSv/year (2/2 medical/natural)

Astronaut out in the storm on 20.01.2005

What about the 100 MeV protons from the 20.01.2005 storm?

- Due to 11 cm water penetration: Shielding is needed
- Shielding of the ISS decreased exposure to $\leq$ 10 mSv
- Standing on the moon, only protected by suit: 500 mSv
- Worse storm on 02.08.1972, right between Apollo 16 and 17 mission
- 4000 mSv on the moon, 350 mSv in the Apollo command module

Compare shielding ($\frac{\mathrm{g}}{\mathrm{cm}^2}$):
ISS: 15 / Apollo module: 7 / Spacesuit: 0,25

Electronic devices are also affected!

No sensitive DNA, but also no mechanism to repair themselves!

Satellite damage

- **Deep dielectric charging:** Creation of large potentials by ionization from the protons.
- **Damage conditions:** Flux of 2 MeV particles $\geq 3 \cdot 10^8$ per cm^2, day and sr for 3 consecutive days
- Consequences: Exceeded breakdown potential, destroyed semiconductors, loss of bits
- Therefore: Usage of 'old fashion computer'

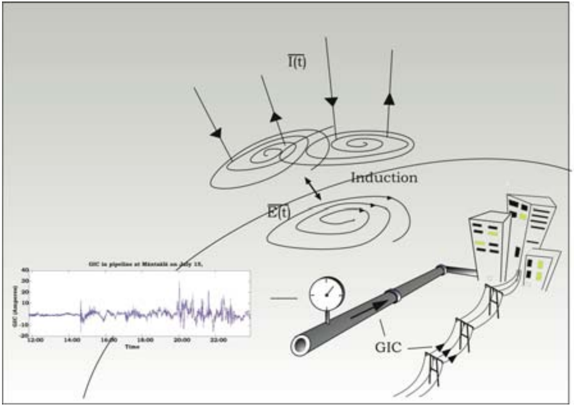
The danger of GICs

During a proton storm: Change in $\vec{B}$.
Faraday's law of induction

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

predicts induced currents...
...if there is a conductor. Is there one on earth which can be used?
Sure! Power transmission grids, oil pipelines, railways, telephone cables...

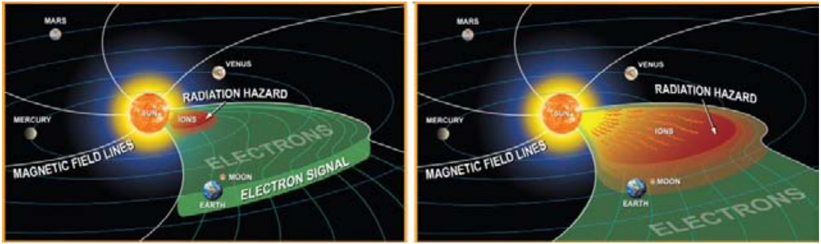
The danger of GICs



What can happen: Loss of power in the Hydro-Quebec power grid for over nine hours on 13 March 1989.

Weather forecast

To prepare for loss of communication and to safe astronauts: Forecast of proton storms needed.



Possible, as radiation and electrons arrive earlier.

Dangerous particles, but beautiful lights

Dangerous particles, but beautiful lights

Green light comes from electron reactions:

$$O(^1S) \rightarrow O(^1D) + \gamma(557,7nm[green])$$

Protons prefer

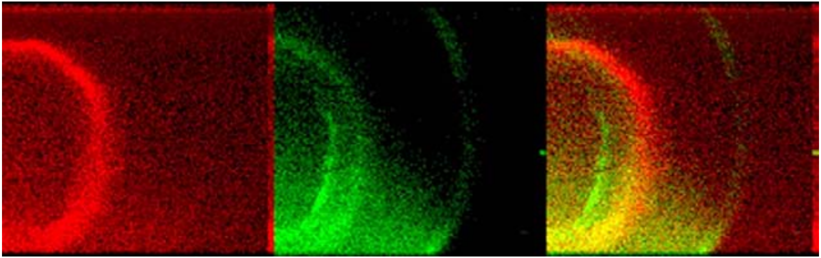
$$N_2 + p \rightarrow N_2^{+*} + e + p$$

but they also induce secondary electrons (N_2^{+*} is an excited vibration state, emits UV light).

Differences between electron and proton Auroras

- **Diffuseness** After neutralization: no alignment along magnetic field.
- **UV light** Most proton events cannot be seen with human eyes

Help: *IMAGE spacecraft*



Arrival in Umeå

Oh, I'm sorry: The protons will never reach the ground :-)
And if one would, you won't realize...