Space Physics 2007
A proton’s way fom the sun to Umeå

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Contents

1 Proton at home

1.1 Its origin

Actually the sun is not the place where protons a created, but the place they start their journey. The sun uses the protons to produce its energy by using the process of fusion. Using Einstein's mass-energy equivalence $E = mc^2$ we know that we can get energy by either splitting a core into two cores with total mass lower than the initial core's (core fission) or by creating a core out of two cores with a mass lighter than the sum of the initial cores (core fusion). The sun uses core fusion to get all its energy. Weizsäcker's formula, which helps us calculating the binding energy of a core, tells us that fusion can only be applied to very light cores. A good candidate for that is Hydrogen: a single proton.
There are two main fusion reactions occurring in the sun:

1.1.1 Proton-proton chain reaction

A proton-proton chain reaction (PPCR) needs less temperature than all other fusion reactions (only 3 million Kelvin). This makes it the most important fusion reaction in the core of the sun. The temperature is needed to fight against the repulsive coulomb force. But what's also needed is the tunneling effect that causes a nonzero probability of fusion even if the kinetic energy of a proton is not enough.
First part of this PPCR is the following:

$$p + p \rightarrow {}^2H + e^+ + \nu_e \tag{1}$$

Weak interaction during the change of a proton into a neutron creates a positron (which will annihilate and release two 511 keV gamma rays) and an electron neutrino, which will pass the sun without interaction. Next step is the following:

$${}^2H + p \rightarrow {}^3He + \gamma + 5,49MeV \tag{2}$$

After this first fusion the PPCR splits up into four different branches. The most probable (91%) is the pp I branch:

$${}^3He + {}^3He \rightarrow {}^4He + p + p + 12,86MeV \tag{3}$$

1.1.2 CNO cycle

The CNO (carbon nitrogen oxygen) cycle plays a more important role for stars with a mass bigger than the suns, thus our sun produces only 1,6 % of its energy by the CNO process.

Here is a list of the reactions of the CNO process:

$$^{12}C + p \rightarrow {}^{13}N + \gamma \qquad +1,95MeV \tag{4}$$
$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e \qquad +2,22MeV \tag{5}$$
$$^{13}C + p \rightarrow {}^{14}N + \gamma \qquad +7,54MeV \tag{6}$$
$$^{14}N + p \rightarrow {}^{15}O + \gamma \qquad +7,35MeV \tag{7}$$
$$^{15}C \rightarrow {}^{15}N + e^{+} + \nu_e \qquad +2,75MeV \tag{8}$$
$$^{15}N + p \rightarrow {}^{12}C + \alpha \qquad +4,96MeV \tag{9}$$

1.2 Saying goodbye to sun

As the protons are brought closer to the suns surface by convection and the density is decreasing, they will finally be able to escape the gravitational force of the sun. An important factor is their high kinetic energy due to the hight temperature of 10^6K in the corona. We call these mass ejections (10^6 tons per second) solar wind, which is in general a movement of protons, electrons, α particles and only a small amount of other types of ions. The solar wind can be divided into *slow* and *fast* solar wind. The slow solar wind has its origin in the suns area of closed field lines. Its speed varies between 250-400 $\frac{\text{km}}{\text{s}}$ and its density is about 11 cm^{-3}. The fast solar wind comes from areas with open magnetic field lines, so called coronal holes, located at the polar caps of the sun. It reaches a speed of about 400-800 $\frac{\text{km}}{\text{s}}$, but has a lower density of only 3 cm^{-3}. The energies associated with those particles vary between 3 eV and 3 keV so they have very low energies. To measure a real big peak in the solar wind, you need the help of some special events: solar flares and coronal mass ejections (CMEs).

1.2.1 High speed due CMEs and solar flares

As the connection between CMEs and solar flares is not completely understood and as both words are often used to describe the acceleration of protons which then set up a *proton storm*, I will now give a short introduction to them.

Solar flares Solar flares are violent explosions at the Sun's corona and chromosphere, which can be found in the area of sunspots. An energy of about $10^{20}\frac{\text{J}}{\text{s}}$ is released, which can be compared with a billion megatons of TNT. Flares are classified due to the peak flux from 10^{-8} till $10^{-4}\frac{\text{W}}{\text{m}^2}$ by A,B,C,M and X flares. The name 'flare' comes from a bright flash of light and X-rays which can be observed from Earth.

CME A CME is a large amount (about 10^{12} kg) of particles (primarily protons) ejected from the Sun's corona. The origin of CMEs is also the area of sunspots. Each day about 1-6 CMEs occur, depending on the phase of the solar circle. The definition of CMEs and solar flares is not very clear. Thus both expressions are often mixed. The first idea of a theory for the CMEs was that they were driven by a solar flare. But today we know that only 60% of solar flares are connected with CMEs and that sometimes CMEs start earlier than the according flare.

Solar flares and CMEs can cause proton storms with a particle speed exceeding 1 MeV. I want to point out one special proton storm with an extreme high kinetic energy.

The great proton storm of 20.01.2005 On January 20th in 2005, a great proton storm with a kinetic energy peak of 100 MeV was observed by the Solar and Heliospheric Observatory (SOHO). Between 15th-19th of January four powerful flares (X-class) from the sunspot 'NOAA720' were observed until the final flare occurred. Researchers wondered about the great amount energy of this storm. It was too high to be released only by a normal CME. One reason might be that there was also a direct connection between NOAA720 and the Earth by the Sun's spiral magnetic field lines.
Now that we know about the origin of high speed protons from we Sun, we have to ask ourselves what they are doing after they were accelerated.

2 Hey proton, where are you going?

Particles coming from the Sun have to follow the spiral of the Sun's magnetic field lines (Parker spiral). So most of the CME and flare events will blast the protons in outer space without our notice. First we have to pick out those who point to Earth. You can get a big increase of intensity if the proton's origin (e.g. a sunspot) is close to the origin of a magnetic field line connecting Sun and Earth (Fig. 1). Before the protons reach Earth to either pass it or crashing into the atmosphere, they might meet an astronaut somewhere in space.

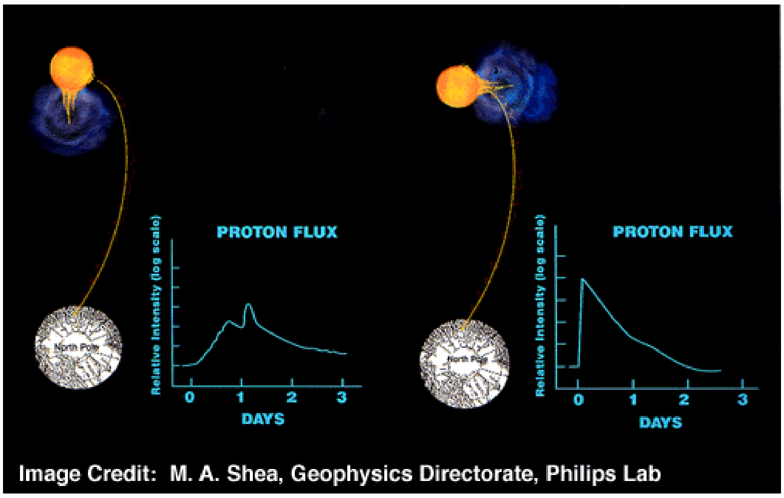

Figure 1: Proton flux depending on the event location

2.1 Humans: Watch out, the protons are coming!

2.1.1 Particles hitting matter

Depending on the energy, all kinds of radiation are able to cause biological damage. When charged particles enter matter, they depose their energy by electromagnetic interaction (light emission by atomic state excitation and ionization). For massive particles like protons, this energy deposition can be described by the *Bethe-Bloch formula*:

$$-\frac{dE}{dx} = D\rho Z^2 \frac{Z_A}{A_A}\frac{1}{\beta^2}\left[\ln\left\{\frac{2m_e c^2\beta^2\gamma^2}{I} - \beta^2\right\}\right]\frac{\mathrm{MeV}}{\mathrm{m}} \tag{10}$$

$D = 0.0307\mathrm{MeV}\frac{\mathrm{m}^2}{\mathrm{kg}}$ ρ : dense of matter $\mathrm{Z_A}, \mathrm{A_A}$: charge and mass number of absorber
Z : particle charge m_e : electron mass
We see that the formula is independent of the particle's mass. Integration guides us to the particles range in matter, called penetration depth. Low energy protons can easily be absorbed by even a sheet of paper. But we'll get a problem when proton energies increase. What can happen if a charged particle makes its way trough the human skin and causes ionization in a cell?

2.1.2 Damage in a cell

If the ionized molecule will not recombine with its lost electron, it might break and new compound can be formed. Those can be toxic for the human cell, like H_2O_2. The worst case cell damage by ionization is a DNA double-strand break. Most cell damage can be repaired by the cell's metabolism or automatic DNA repairing, but not a double-strand break. The consequence can be a death cell or - even worse - a mutating cell which might cause cancer.
The damage done by radiation has do be classified. The *absorbed dose* tells us about the energy deposited per mass unit in a medium. Its unit is 'Gray':$1\mathrm{Gy} = 1\frac{\mathrm{J}}{\mathrm{kg}}$. The absorbed dose does not give us enough information about cell damage. There is a dependency of the kind of radiation: protons have a higher ionization density than photons and cause - with same absorbed dose - a 5 times higher damage. So a new measure is introduced: the *equivalent dose*. It is just the absorbed dose multiplied with a factor depending on the kind of radiation. For a proton, it is 5. The unit of the equivalent dose is 'Sievert' (Sv). You can specify the damage even more precisely by using the *effective dose* which also considers the type of organ being damaged.

2.1.3 The astronaut's damage caused by solar protons

If the dose for a human body exceeds 200 mSv, a change in the astronaut's health can be diagnosed in a change of blood count. As the dose increases, astronauts will get a *radiation sickness*: A few days after the radiation exposition the following symptoms will appear: vomiting, fatigue, low blood counts, temporary male sterility. The real sickness occurs at 1-2 Sv (*light radiation poisoning*, 10% fatality after 30 days) and gets worse at 2-3 Sv (*moderate radiation poisoning*, 35% fatality, loss of hair all over the body) and 3-4 Sv (*severe radiation poisoning*, 50% fatality, uncontrollable bleeding). A dose with more than 6 Sv need intense medical care (bone marrow transplant).

The average dose humans on Earth are exposed is 4 mSv per year, 2 mSv caused by natural radiation like cosmic and terrestrial radiation and additional the civil radiation which is in general medical exposition (also 2 mSv). The amount of radiation from nuclear power plants, industrial work and other kinds of radiation can be neglected. Now we'll see which doses astronauts can expect. Let's have a look at the proton storm of January 20th in 2005:
In principal, 100 MeV protons are able to burrow through 11 cm of water, so shielding for the astronauts is really needed. As they stayed within the ISS spaceship, which is well shielded by its own shielding and also by Earth's magnetic field, they did not absorb more then 10 mSv. The situation looks different for an astronaut standing on the moon with his space suit as the only protection. He would have received 0,5 Sv. This does not seem to be critical.
But in the past there have also been even worse proton storms powerful enough to thread an astronaut with 4 Sv or more. On the 2nd of August 1972 such a storm occurred. It was the time right between the Apollo 16 and 17 missions, so everyone was at the safe Earth this time. If there were astronauts in space at that time, they should have hidden in the Apollo command module, because it would have decreased the radiation dose from 4000 mSv down to 350 mSv. Compared to the old Apollo shielding with a thickness of $7-8\frac{g}{cm^2}$ the modern ISS shielding has $15\frac{g}{cm^2}$, but a typical spacesuit has only $0,25\frac{g}{cm^2}$. So whenever astronauts go out into space, they should check the space weather first.
Such proton storm predictions are possible as the electrons of the CME are faster due to their smaller mass and in this way they are a kind of forerunner of the proton storm (Fig. 2). Arik Posner from NASA find a way make a reliable ion storm forecast by evaluating the electron flux data by the COSTEP instrument on board SOHO. So serious threat of the astronauts due to protons can be avoided efficiently.

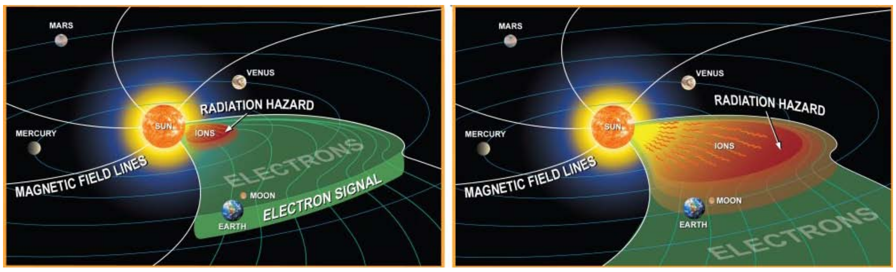

Figure 2: Electrons as forecaster

2.1.4 People in planes

You don't have to be an astronaut to be affected by solar cosmic rays. The higher you get in the atmosphere, the larger the radiation exposure will be: it increases from 0,4 mSv/a at 1000m till 1,1 mSv/a at 3000m. So a flight in a plane is always connected to a radiation dose. Let's look at some example flights:

Frankfurt - Palma de Mallorca - Frankfurt	0,006 mSv
Frankfurt - New York - Frankfurt	0,1 mSv

The complete exposure for an aircrew having 600 h/a at an altitude of 10 km at a latitude of more than 50° N is estimated to be less than 3 mSv/a.
Nowadays it is common for the airlines to check the space weather in the northern hemisphere to adjust their flight routes.
You can compare the exposure with those of the flight of a space mission like Apollo XI, which was 6 mSv during a flight time of 195h. The largest amount of radiation comes from the flight through the Van-Allen belt.

2.2 Disturbing electronics

2.2.1 Satellite damage

Even if an electronic device does not seem to be as complex as a human cell, it can also be damaged by protons coming from the Sun. And as we have limits for radiation sickness for humans, something similar exists for electronic deviced in space (mainly in satellites). We say that the damage conditions are reached when the flux of particles ≥ 2 MeV per cm^2, day and sr is either greater than $3 \cdot 10^8$ for 3 consecutive days or greater than 10^9 for a single day. What happens to the electronic device is called *deep dielectric charging*: the protons penetrate the hull of the satellite up to the circuit board. There very large electric fields can be created, exceeding the breakdown potential and destroying semiconductors. The risk of such damage increases as the complexity of the electronic equipment grows and the critical dimension of transistors is getting smaller. So you will never find a modern computer processor in a satellite; 'old fashion' equipment is preferred.
Even if an incoming particle does not destroy a complete circuit, it can still cause a loss of data by changing the value of a memory bit (which is generally nothing else than a stored capacity).

2.2.2 The danger of GICs

Geomagnetic storms are in general a change of the Earth's magnetic field. As known from Faraday's law of induction, a change in a magnetic field always induces an electric field. If there is a conductor on Earth (this can be e.g. power transmission grids, oil pipelines, railways or telephone cables) you can also have a current which is called GIC (geomagnetically induced current). They are mostly observed in the northern hemisphere and can reach a maximum of tens to hundreds of amperes.
On March 13th in 1989 a geomagnetic storm caused a big GIC in the Canadian Hydro-Quebec system. As a consequence six million people suffered from a loss of power for nine hours. Since this event power companies made a lot of effort to protect their grids from GICs.

2.3 Dangerous particles, but beautiful lights

Now as you know how mad protons can be, we should consider some of their nicer aspects. The *Aurora Borealis* is quite popular and often seen, most times associated with a green looking curtain. But both color and shape are caused mainly by electrons, not protons. The green color comes from a change of oxygen state

$$O(^1S) \rightarrow O(^1D) + \gamma(557,7nm[green]) \quad (11)$$

which was induced by an electron-oxygen reaction. Protons have another 'main line'. They prefer the following reaction:

$$N_2 + p \rightarrow N_2^{+*} + e + p \quad (12)$$

The N_2^{+*} state is excited namely to a first vibration state. Relaxation of this state gives us a 391,4 nm photon. So the wavelength of the primary proton aurora light is ultraviolet, invisible for our eyes.
Does this mean that we won't see anything from a proton aurora? No! A lot of *secondary electrons* will be released during ionization of atmospheric atoms by the proton. Those can react in the same was as 'normal' primary electrons. If we want to see the additional effects caused by the protons, we need the help of some UV cameras. The *IMAGE spacecraft* has good equipment for such observations. Figure 3 shows us 'proton light' on the left, 'electron light' in the middle

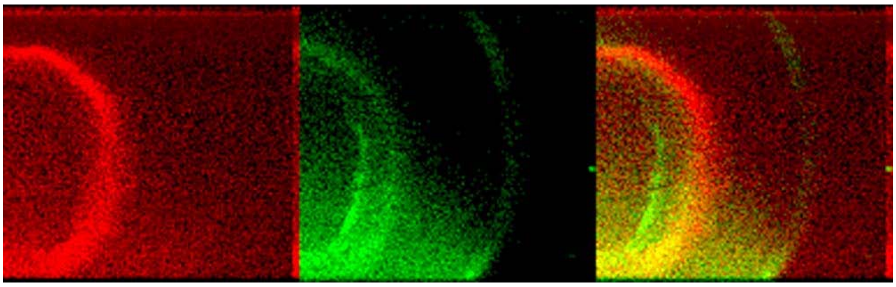

Figure 3: Comparison of electron and proton aurora by IMAGE

and an overlay of both on the right side.
One main difference between proton auroras and normal auroras is the diffuseness of the proton auroras. During their way through the atmosphere, the protons can recombine with electrons. As a neutral hydrogen atom, they are no longer captured by the magnetic field lines. They get ionized and recombine a couple of times while their track becomes more and more diffuse. So proton auroras are usually not that bright as electron auroras and also they don't have a typical curtain shape.

3 The proton in Umeå

Unfortunately, the journey of our protons end before they can reach Umeå. Most of the protons coming from the Sun are not ejected in the Earth's direction. Most of those who are get deflected by the Earths magnetic shield. And if there is a gap in the magnetic shield and they enter the atmosphere, they are just absorbed before they reach the ground.
If we want to meet some protons, we must take a flight by airplane or spacecraft. But always consider the space weather before you go out. Too many protons might make you feel sick!

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