Elementary Particles and Cosmic radiation

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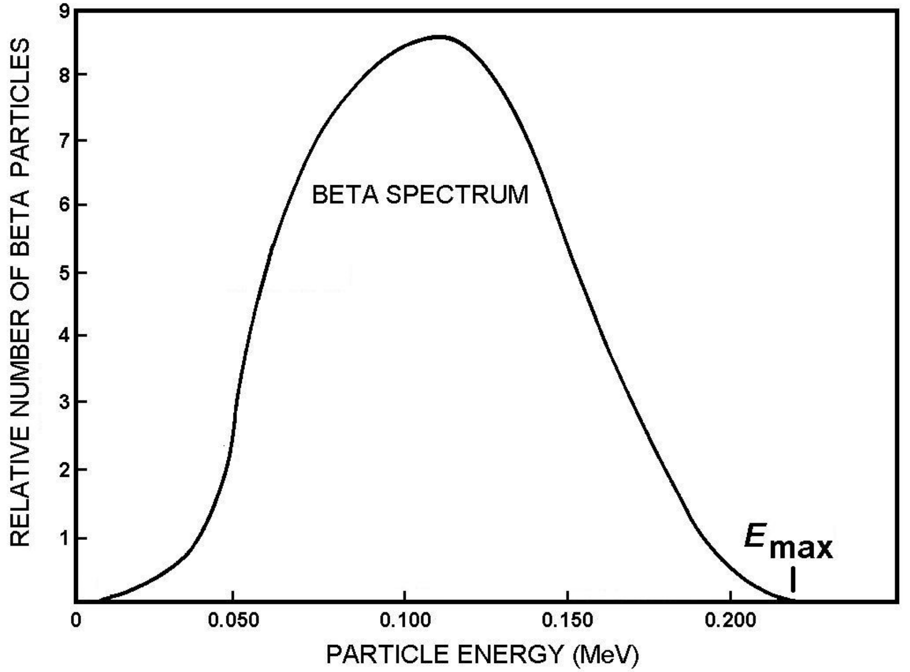
Basic elementary particles

Three types of basic elementary particles have been known for a long time. They are the building blocks of normal atoms:

- Electrons; e^-, in the electron shell
- Protons; p^+, in the nucleus – defines the element
- Neutrons; n, uncharged – stabilizes the nucleus by ”diluting” the positively charged protons.

Beta-decay energy

All nuclear decay reactions are quantified. Hence a specific beta-decay should always produce beta particles with the same energy. However, this is what is observed. E_{max} is the beta-decay energy.



Where does the missing energy go?

Neutrinos

I have done a terrible thing today, something no theoretical physisist ever do.

I have suggested something that can never be verified experimentally.

W. Pauli, 4 dec. 1930.

The neutrino explained the electron energy in beta decay. It also gave a plausible explanation of how the beta particle could be formed by the atomic nucleus, and it explained why it looked like as if energy disappeared without trace in the beta decay of a nucleus.

Neutrinos are generated in the sun by e.g.: $p + p \rightarrow d + e^{+} + \nu$

The intensity of neutrinos on Earth is estimated to be 10^{15} $m^{-2}s^{-1}$. Of these, about 85 % is from the reaction above.

Pauli never believed that it would be possible to detect a neutrino. Several light-years of lead would be needed to stop it (1 ly ~ 10^{16} km). The reason we can detect neutrinos is through their reaction with other matter. Most commonly used is: $^{37}Cl(\nu, e^{-})^{37}Ar(EC, 35d)^{37}Cl$. Separated Ar is detected by its decay.

The neutrino is the most common particle in the Universe. It is 10 times more common than photons, which in their turn is 10^{9} times more common than protons and neutrons. It is designated by ν (greek n).

Neutrinos cont.

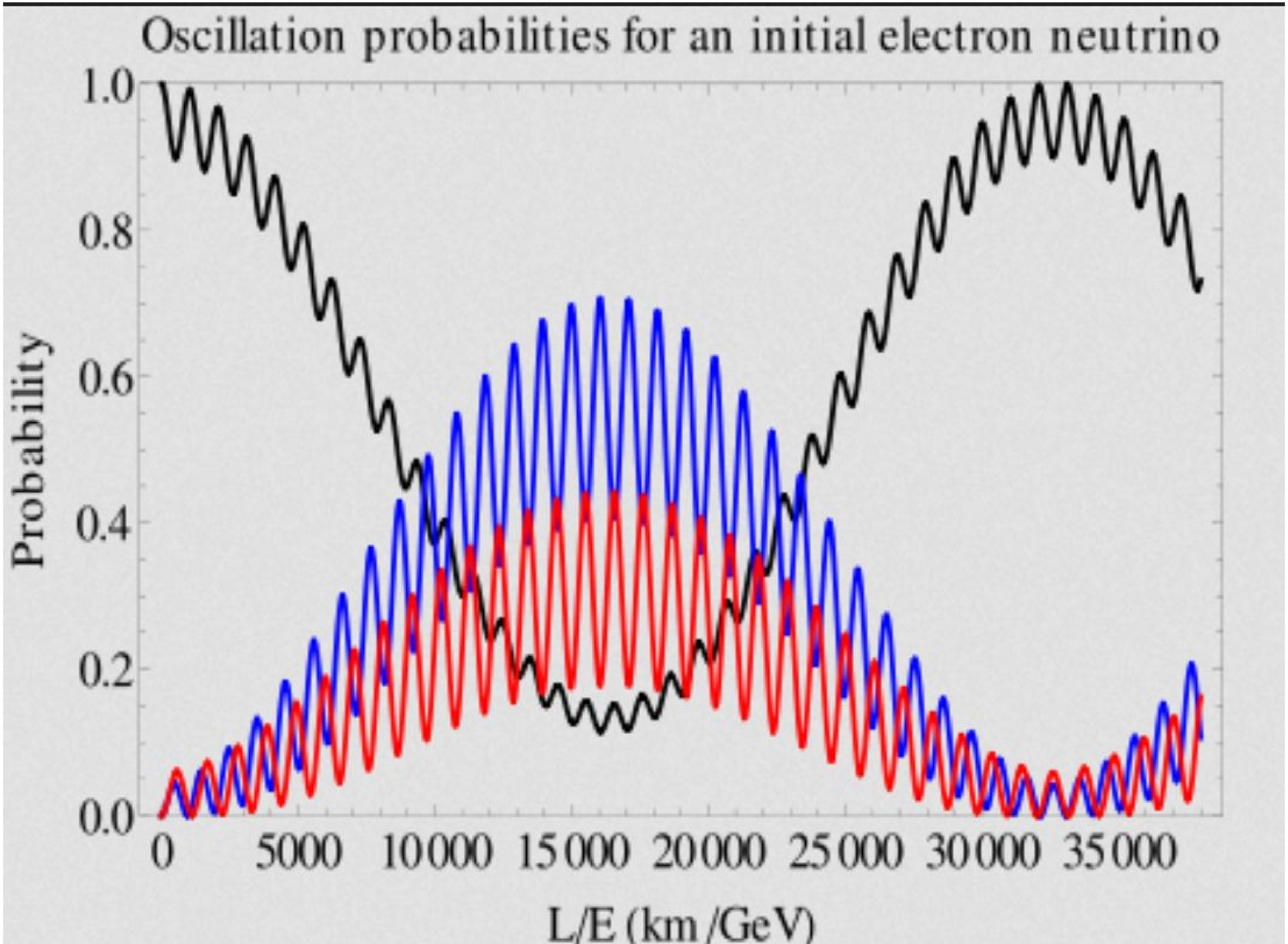
Measurements by the Cl-method show that the neutrino flux on Earth fom the sun is only 1/3 of the theoretically expected value. The reason is that some neutrinos change type during passage out through the sun. Verified by new measurements using D_2O detector in Canada which can measure lower ν-energies.

At 07.35.35 GMT on 23rd february 1987 a strong neutrono puls was recorded by several detectors. About 18 hours later it was seen that a supernova had exploded, SN1987A.

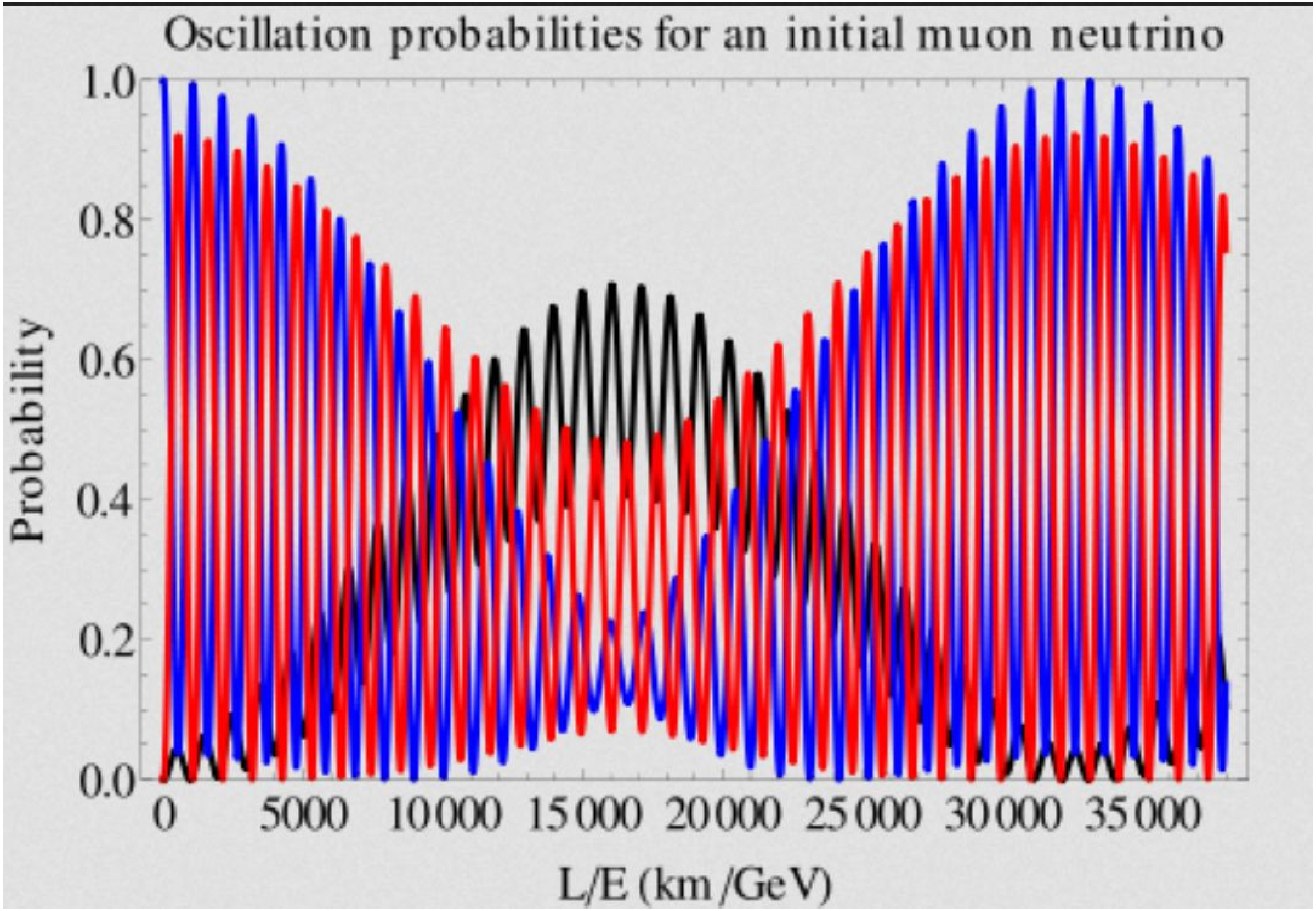
The delay of light is caused by the very small amount of matter in interstellar space. Hence, the speed of light in interstellar space was less than c_o.

Because the neutrinos move with the speed of light, c_o, they arrived before the photons.

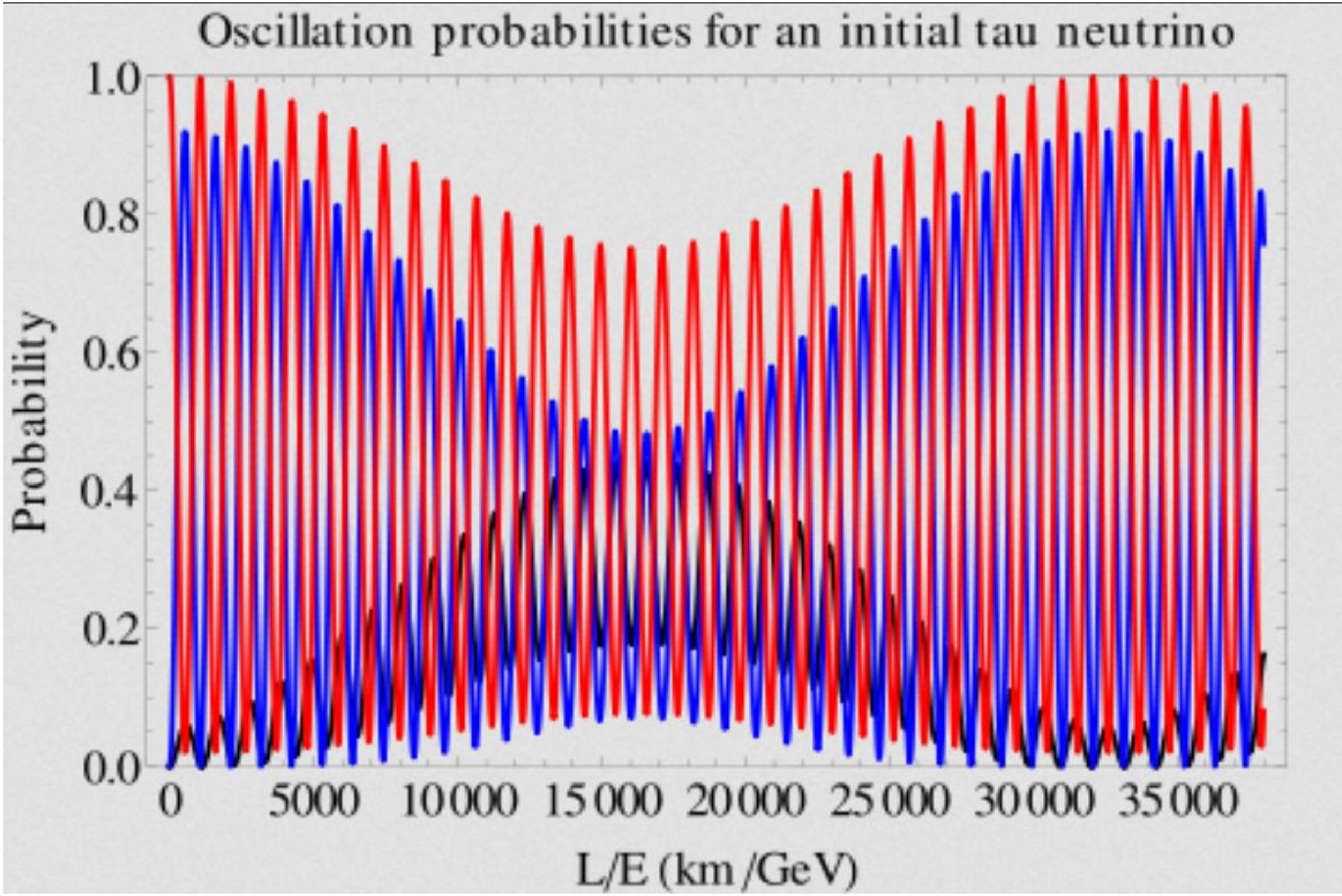
There is at least three types – Flavors - of neutrinos: electron neutrinos, muon neutrinos, and tauon neutrinos. The neutrino oscillates between the three flavors by trading mass and kinetic energy.



FLAVORS: black = e-neutrino, blue = muon-neutrino, and red = tau-neutrono



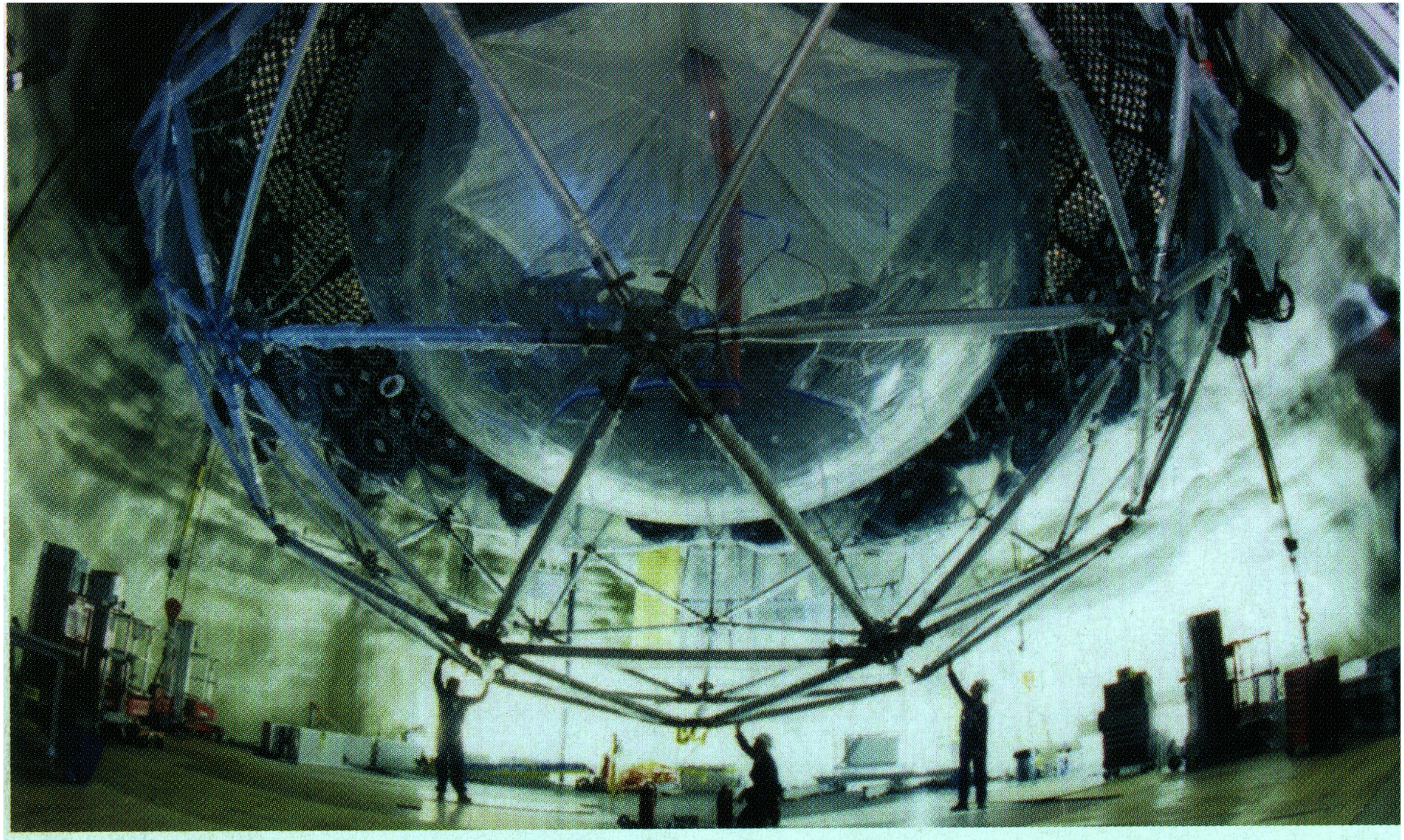
FLAVORS: black = e-neutrino, blue = muon-neutrino, and red = tau-neutrono



FLAVORS: black = e-neutrino, blue = muon-neutrino, and red = tau-neutrino

The Neutrino Observatory in Sudbury

2 km below surface, contains 10^6 kg D_2O



The Sudbury Neutrino Observatory has proven, almost beyond doubt, that neutrinos switch flavour – solving the solar neutrino problem. Pictured is the detector under construction. Image: SNO.

The Dirac wave equation and antimatter

The well known Schrödinger equation is only valid in a universe where the speed of light is infinite (i.e. m is constant at any speed). In 1928 Dirac published a new wave equation which is valid in a relativistic universe where the speed of light is finite.

$$\left(i\gamma^\mu \frac{\partial}{\partial x^\mu} - \frac{mc}{\hbar}\right)\psi(x) = 0$$

The solution of this equation for the rest energy of an electron is a square root of a number of variables. Initially only the root which gave a positive rest mass was accepted. However, Dirac realized that the negative root could describe a universe with all particle positions filled, but at negative rest mass. Addition of sufficient energy to a point could then produce a particle with positive mass and a hole in the negative mass matter. A particle and its antiparticle were then formed as a pair. The first antiparticle, β^+, was discovered ~2 y later.

The solution of the Dirac wave equation for the total energy, W, of a free electron looks formally as follows (from my old swedish textbook in nuclear chemistry);

$$W = \pm \mathbf{c} \, (p_1^{\,2} + p_2^{\,2} + p_3^{\,2} + m^2\mathbf{c}^2)^{1/2}$$

where the p:s are parameters, **c** the speed of light in vacuum, and m the electron mass.

Hence, it is believed today that any kind of particle has a corresponding antiparticle.
In special cases, the particle is its own antiparticle (e.g. photon)

Solutions to the Dirac equation the are 4-dimensional wave functions, and **elementary particles have no intrinsic spin**.

Elementary Particles (disregarding Dirac)

Fermions: matter particles (have spin ½, 3/2, 5/2, …)

- baryons: can feel the strong interaction
  - Quarks: up, down, charm, strange, top, bottom quarks and their anti-particles
- leptons: does not feel the strong interaction
  - electron, muon, tachyon, their neutrinos and anti-particles

Bosons (force carriers)

- with spin 1, 2, …
  - gravitons, photons, W-bosons, Z-bosons, gluons, Mesons
- with spin 0
  - Higgs particle(s) (give the other particles their mass)

Elementary Particles

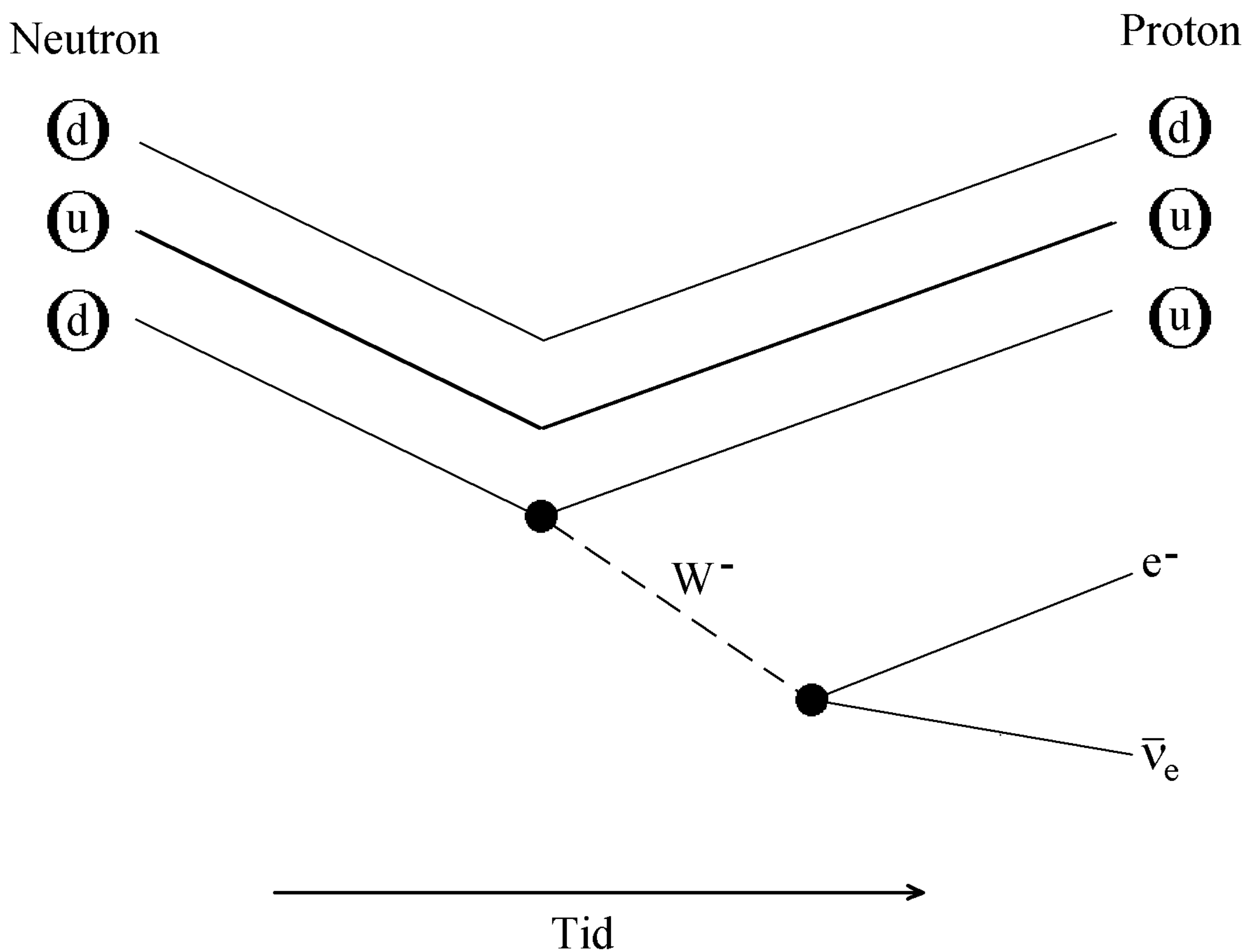
Particle	Rest Mass (u)	Charge (e)
Up Quark	1/3	+2/3
Down Quark	1/3	-1/3
Charm Quark	1.61	+2/3
Strange Quark	0.54	-1/3
Topp Quark	188.5	+2/3
Bottom Quark	4.83	-1/3
v_e (electron neutrino)	$< 2 \times 10^{-8}$	0
v_μ (muon neutrino)	~ 0	0
v_τ (tauon neutrino)	~ 0	0
e (electron)	0.0005486	-1
μ (muon)	0.114	-1

The ”Standard Model”

Proton = 2 up-quarks + 1 down-quark
Charge = 2 x +2/3 – 1 x (-1/3) = +1
Mass = 2 x 1/3 + 1 x 1/3 = 1

Neutron = 1 up-quark + 2 down-quarks
Charge = +2/3 – 2 x (-1/3) = 0
Mass = 1 x 1/3 + 2 x 1/3 = 1

Neutron beta-decay



Many Worlds Interpretation of Wave Function Collapse

In his thesis 1957 Hugh Everett showed that the derivation of the general relativity theory by Einstein implicitely assumed that the observer is outside of our universe. When the observer in inside the universe the solutions are slightly different.

One possible interpretation of these solutions is that the universe ”splits” each time a probabilistic quantum event occur.

This removes many problems e.g. Schrödinger's cat experiment, the EPR paradox, von Neumann's "boundary problem", and even the wave-particle duality. Quantum cosmology also becomes intelligible, since there is no need any more for an observer outside of the universe.

Forces in Nature

Gravity
Acts between all matter
Additive and always attractive
Infinite range
Probably no saturation (Black Holes)
Transmits at the speed of light
$F=km_1m_2/r^2$ with $6.673\cdot10^{-11}$ m^3/kgs^2

Electromagnetic Force
Acts between charged bodies
Additive, but attractive and repulsive
Infinite range
Saturates perhaps?
Transmits at the speed of light
$F = -kz_1z_2/r^2$, k depends on the medium

Strong Interaction
Acts between hadrons (baryons, mesons)
Saturates
Short range, $<10^{-14}$ m
Transmits rapidly (action time $<10^{-23}$s)
Exists inside the atomic nucleus

Weak Interaction
Acts on leptons (e, muons, neutrinos)
Also acts between leptons and hadrons
Slow action, 10^{-9} s
Limited range, 10^{-15} m

Dark energy
???

Forces in Nature

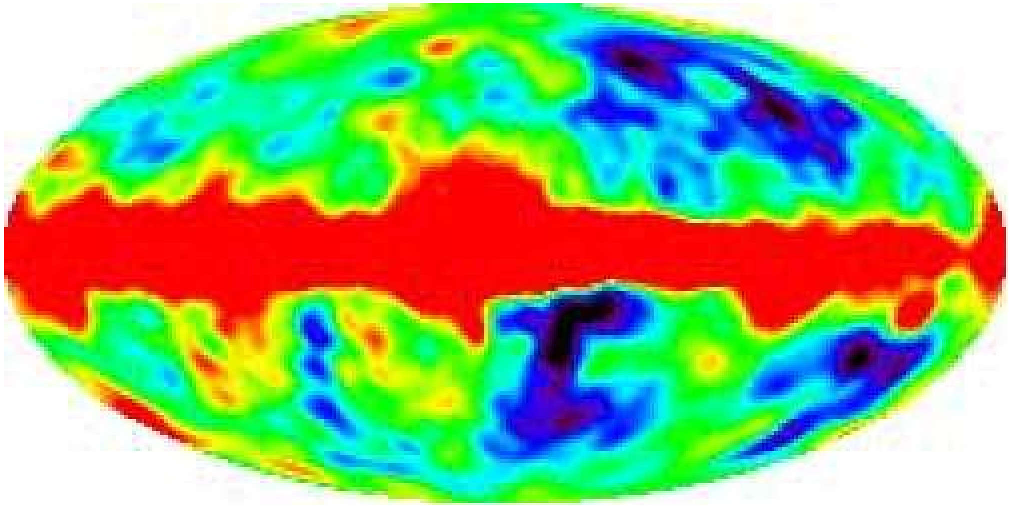
Relative Strengths

1.	Gravity	1	x gravity
2.	Weak interaction	10^{25}	x gravity
	Electromagnetic force	10^{36}	x gravity
3.	Strong interaction	10^{38}	x gravity
4.	Dark energy	?	x gravity

Dark energy only acts over enormous distances and its strength might vary with time. At present it increases the expansion rate of the Universe, and opposes gravity over very large distances.

Cosmic radiation

In 1911 V. F. Hess discovered that background radiation increased with altitude when he sent up a radiation detector in a baloon. Hence it was found out that background radiation not only originates from radioactive elements on Earth but also arrives from space – cosmic radiation. It was soon discovered that the intensity of the cosmic radiation varies both with altitude and place on Earth.



Map of intensity variations in the cosmic background radiation from COBE satellite data. The hot red band across the equator is the plane of our galaxy. Fluctuating emissions from the edge of the visible universe dominate regions away from the equator. Courtesy: NASA

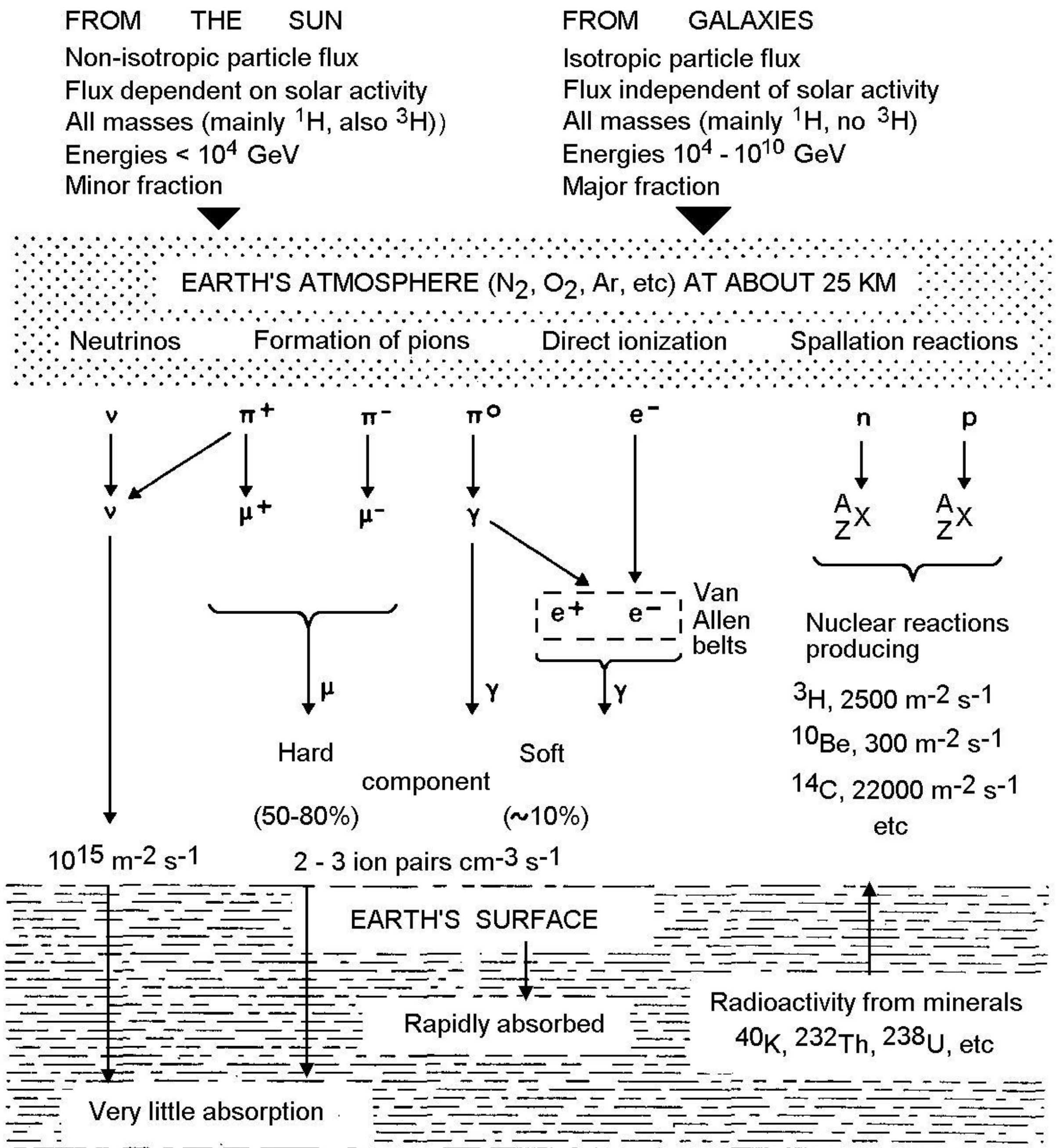
Cosmic Radiation

In order to describe the cosmic radiation, it is important to differentiate between primary and secondary radiation.

Primary radiation is:
- Electromagnetic radiation
- Particle radiation
- Neutrinos

Secondary radiation: When primary radiation hits the atmosphere as particles or photons it gives rise to a large number of secondary particles due to its very high initial energy. The majority of initial secondary particles are pions. They are short-lived and decay into muons and pions.

Cosmic radiation creates 2-3 ion pairs per cm^3 and s at the Earth’s surface (varies during the sunspot cycle).



FROM THE SUN
Non-isotropic particle flux
Flux dependent on solar activity
All masses (mainly ^1H, also ^3H))
Energies < 10^4 GeV
Minor fraction
FROM GALAXIES
Isotropic particle flux
Flux independent of solar activity
All masses (mainly ^1H, no ^3H)
Energies 10^4 - 10^{10} GeV
Major fraction
EARTH'S ATMOSPHERE (N_2, O_2, Ar, etc) AT ABOUT 25 KM
Neutrinos
Formation of pions
Direct ionization
Spallation reactions
ν
π^+
π^-
π^0
e^-
n
p
ν
μ^+
μ^-
γ
^A_ZX
^A_ZX
e^+
e^-
Van Allen belts
Nuclear reactions producing
μ
γ
γ
^3H, 2500 m^{-2} s^{-1}
^{10}Be, 300 m^{-2} s^{-1}
^{14}C, 22000 m^{-2} s^{-1}
etc
Hard
Soft
component
(50-80%)
(~10%)
10^{15} m^{-2} s^{-1}
2 - 3 ion pairs cm^{-3} s^{-1}
EARTH'S SURFACE
Rapidly absorbed
Radioactivity from minerals
^{40}K, ^{232}Th, ^{238}U, etc
Very little absorption

Electromagnetic Radiation

Initially from the sun, other stars, galaxies, and the Big Bang. This radiation spans the whole electromagnetic energy spectrum form high energy gamma radiation to low energy long-wave radiation.

It is estimated that the Universe in average contains about 400 photons/cm^3. We are also surrounded by a ”sea” of photons with wave-lengths from 0.1 mm to 10 cm arriving with almost the same intensity from all directions. This radiation corresponds to black-body radiation at 2.7 K and is assumed to remain from the Big Bang, and doppler-shifted to this low energy when space expands.

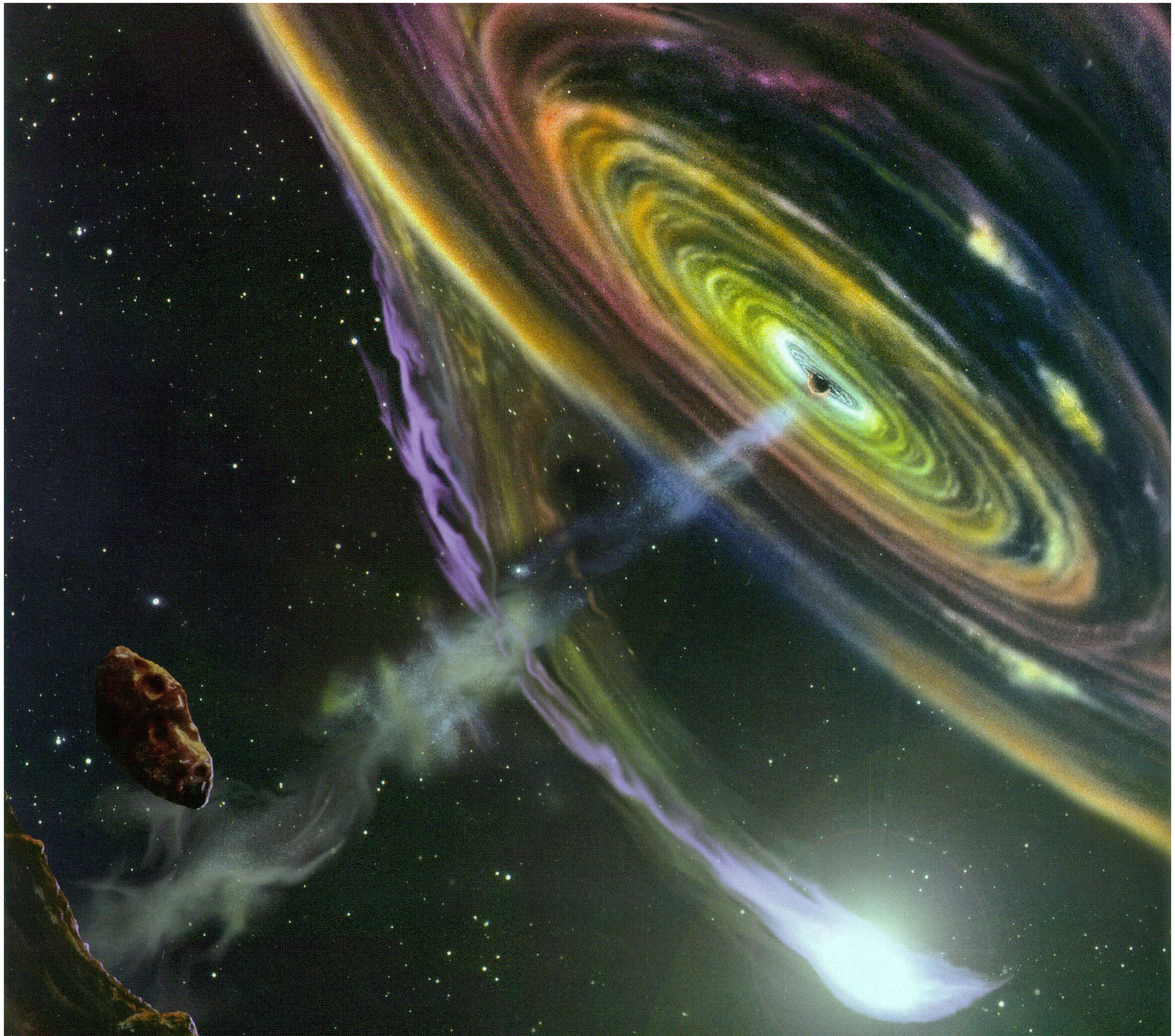
Radiation from the sun is equivalent to black-body radiation at 6000 K. At the surface of the Earth, the spectrum is modified by absorption in our atmosphere.

Gamma Ray Bursts

- Short (1-100 ms) pulses of intense γ-radiation
- Sorces: most probably neutron stars which are ripped apart by nearby black holes.
- Emitted radiation seems to cover a space angle of about 3 % in each of two opposite directions.
- Usually these events are observed in other nearby galaxies and the rapidly fading afterglow from the source in visible light has often been observed.
- In case such an outburst should occur in our galaxy and the radiation hit us, it would be a complete disaster for our atmosphere. The risk is real, but its size is uncertain.

A Gamma Ray Burst

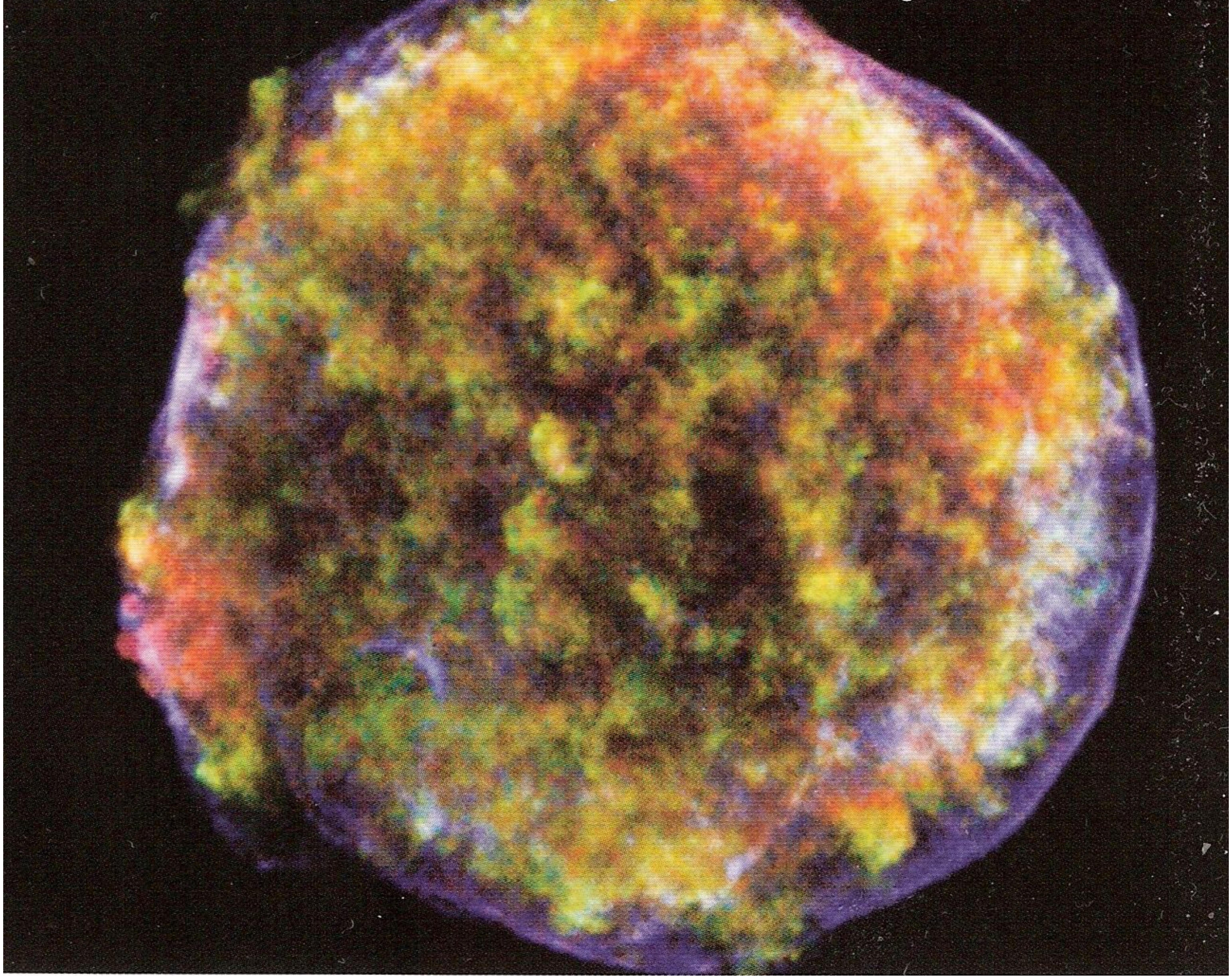
As pictured by an artist



Even the Earth emits x-rays and hard γ-rays to space in short bursts. Discovered by x-ray and γ-ray-burst recording satellites. The mechanism is unknown, but large thunderstorms are suspected to be a possible source (lightning strikes?).

Some γ-rays of high energy are also believed to be accelerated by the shock-wave from supernovas (”ping-pong” Fermi acceleration).

The origin of the majority of high energy γ-rays is still unknown because earlier theoretical explanations have now been falsified by data from new observations (2009).



■ A Chandra X-ray image of Tycho's supernova remnant. Evidence had been found here of cosmic ray acceleration. Image: NASA/CXC/Rutgers/J Warren and J Hughes et al.

Particle Radiation

Composition: All mass numbers, but most ^{1}H

Sources: The Sun

- The smaller part, non isotropic (directional), mostly ^{1}H, but also ^{3}H, $E < 10^{7}$ MeV (causes also the north and south polar lights)

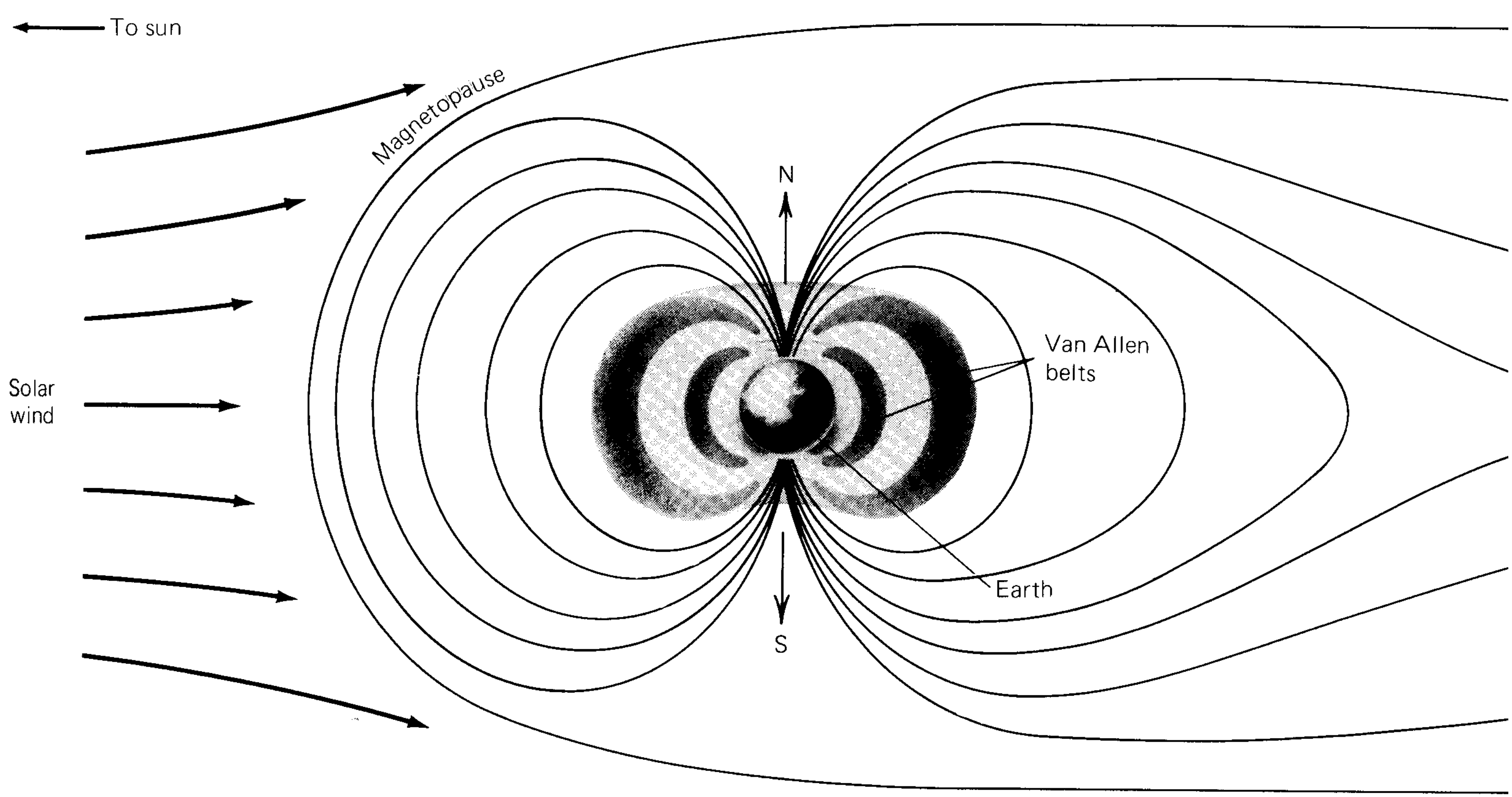
Other nearby stars

Galaxies:

- The major part, isotropic (same from all directions), mostly ^{1}H, no ^{3}H, Energies from 10^{7} to 10^{13} MeV

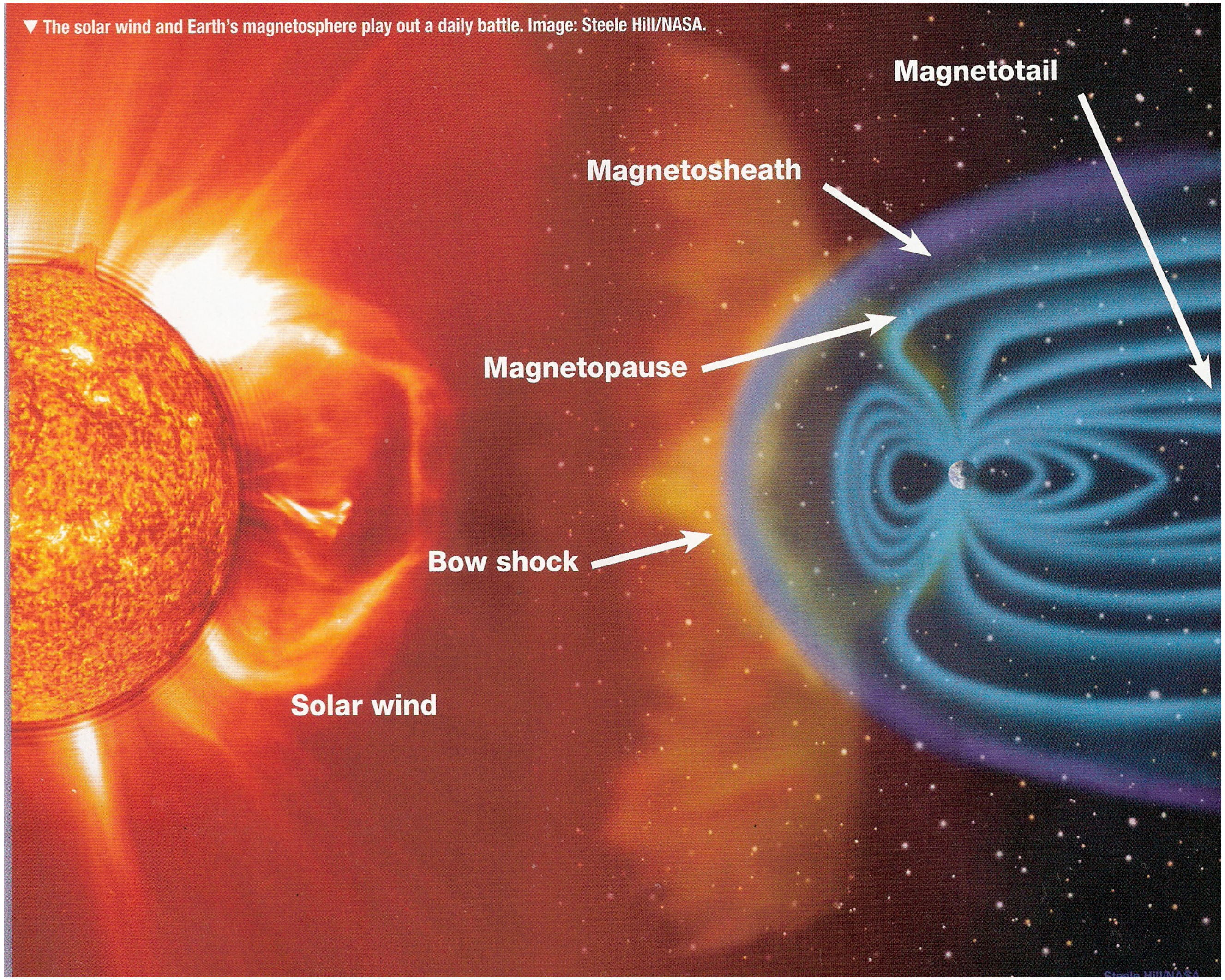
It is believed that particle radiation from galaxies is generated by acceleration in varying magnetic fields and the galaxy's rotation.

The van Allen Belts around Earth



Cross section of the Earth's magnetosphere and the Van Allen belts, as revealed by numerous spacecraft.

The magnetic bubble around the Earth

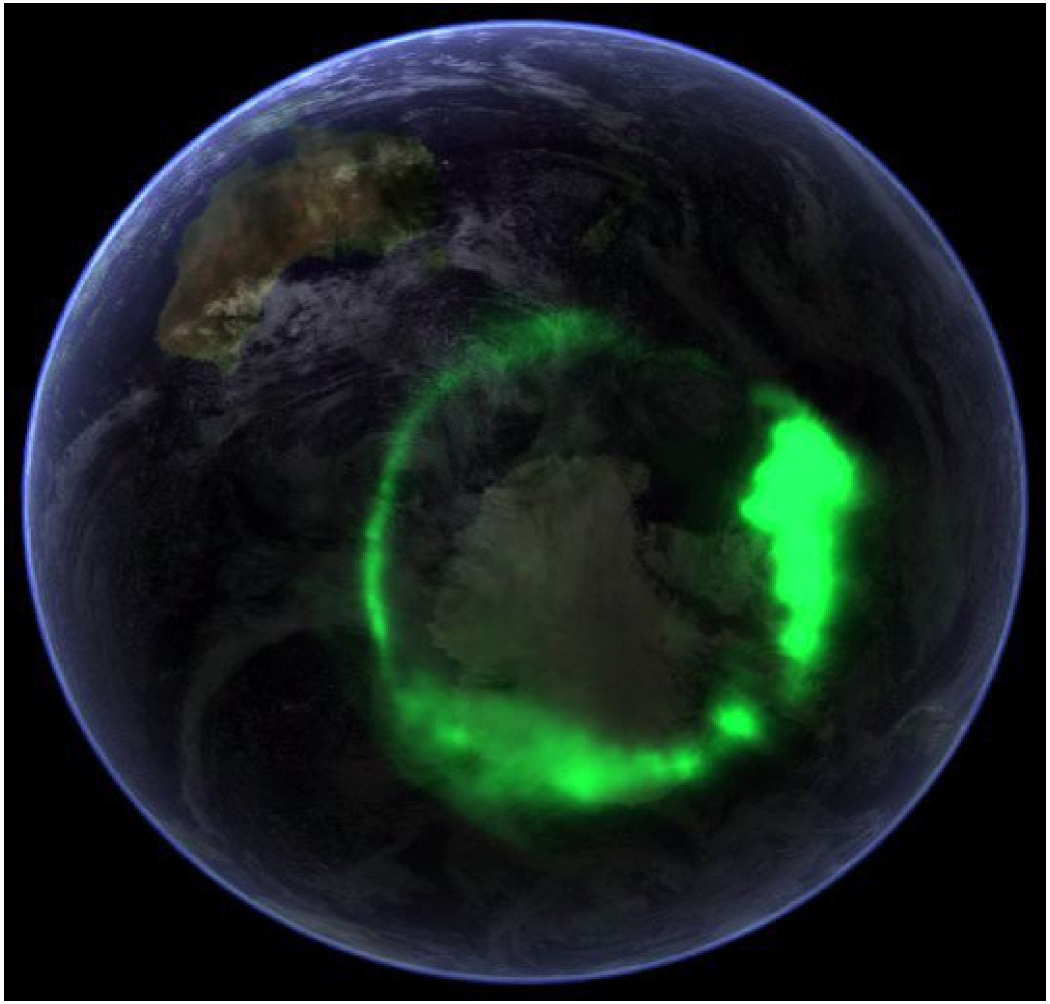


Northern Lights (Aurora)

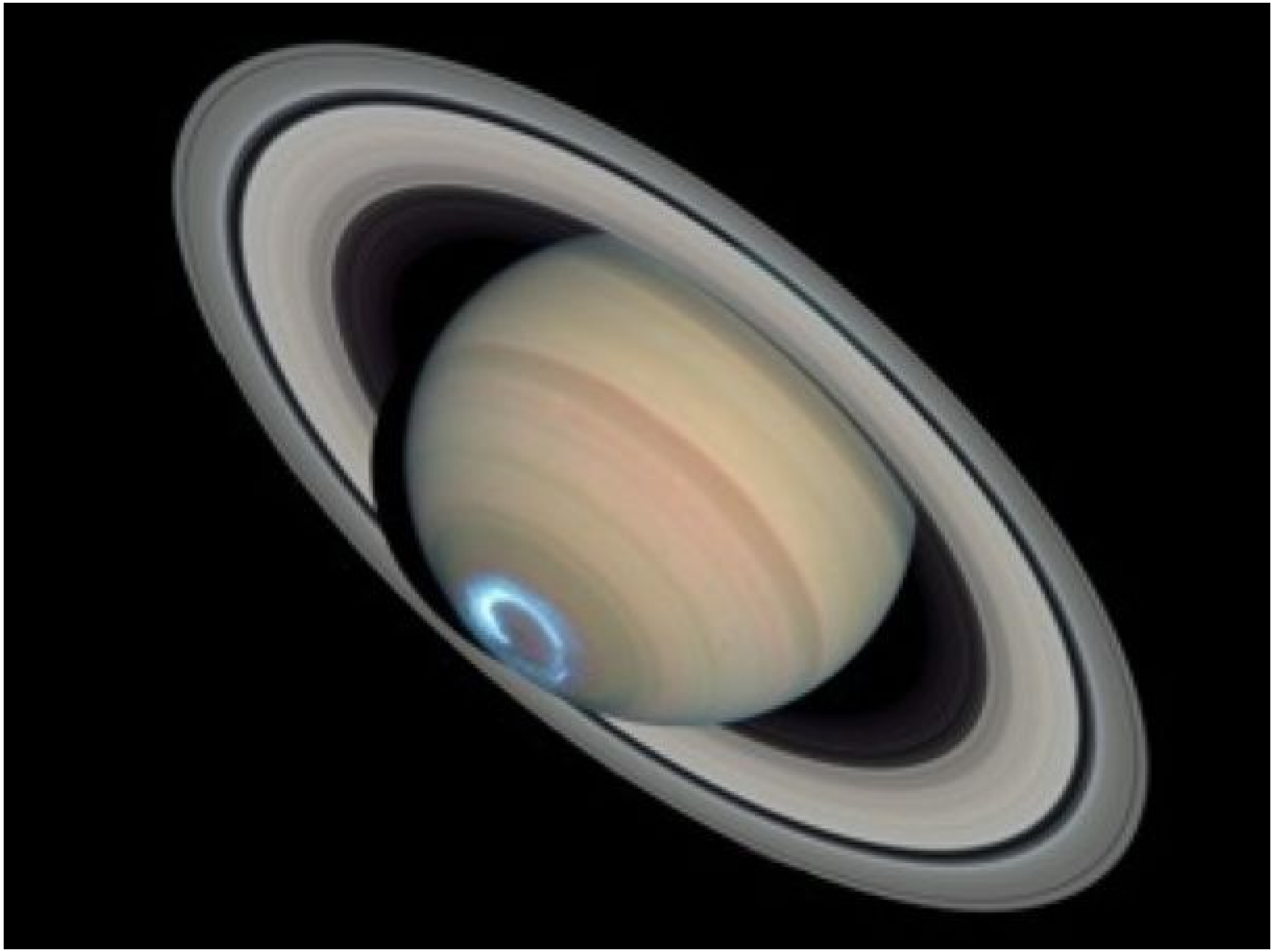
In space, outside our atmosphere, and in the magnetosphere there is a plasma of fast charged particles. During so called magnetic storms it is possible for these particles to descend into the atmosphere. The particles react with, excites, the atoms they encounter. When the excited atoms de-excite light is emitted. The yellow-green color often seen originates from de-excitation of atomic oxygen.

Aurora in Canada

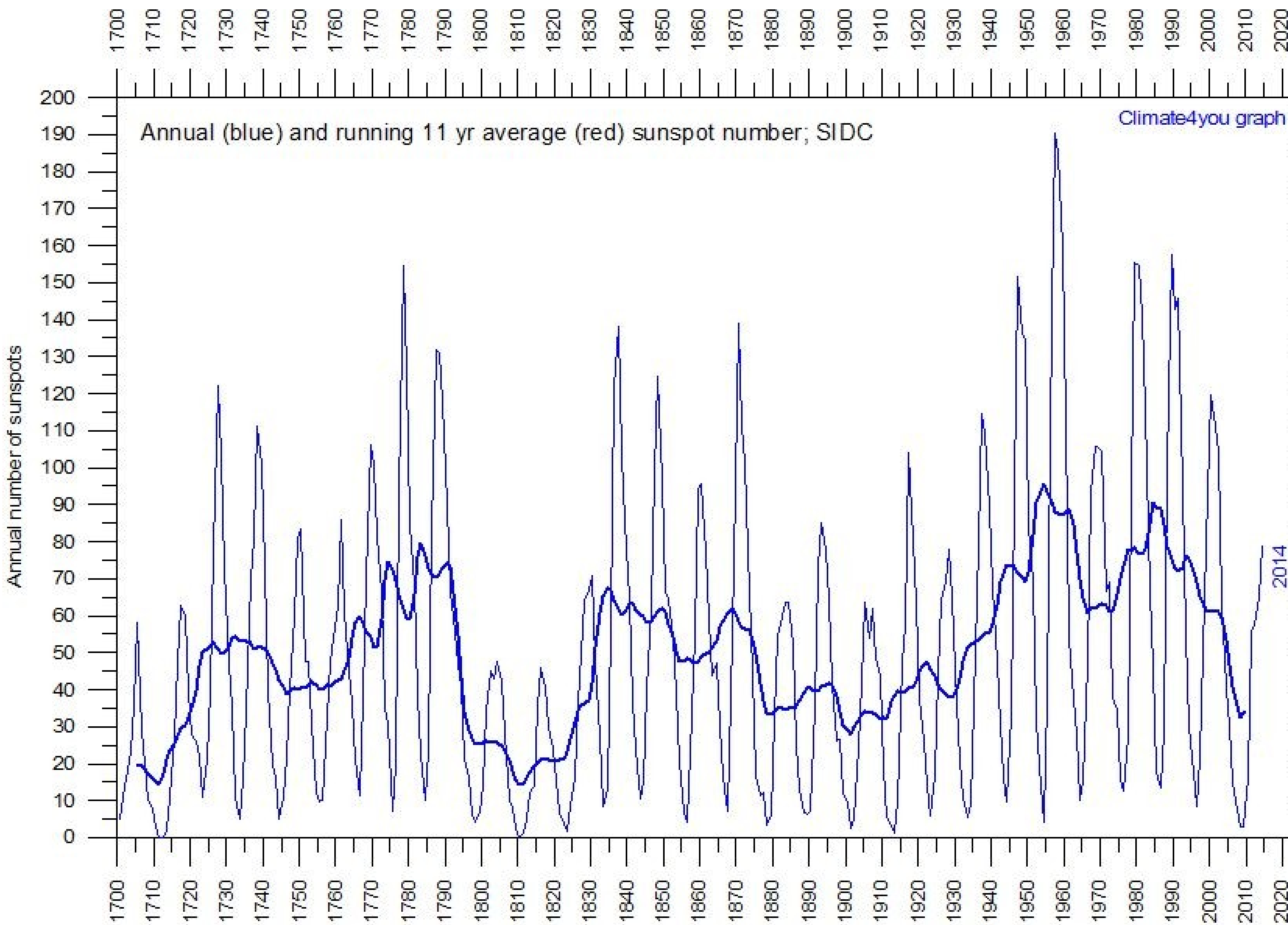
Aurora on Earth seen from space



Aurora on Saturn



At present the suns magnetic field and the solar wind is incresing from a minimum. More new solar spots are seen. The increasing magnetic field forces many particles from outside the solar system to deviate. This affects the occurance of polar lights and also to some extent the cosmic radiation level at the surface.


Annual (blue) and running 11 yr average (red) sunspot number; SIDC
Climate4you graph
Annual number of sunspots
2014
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
1700
1710
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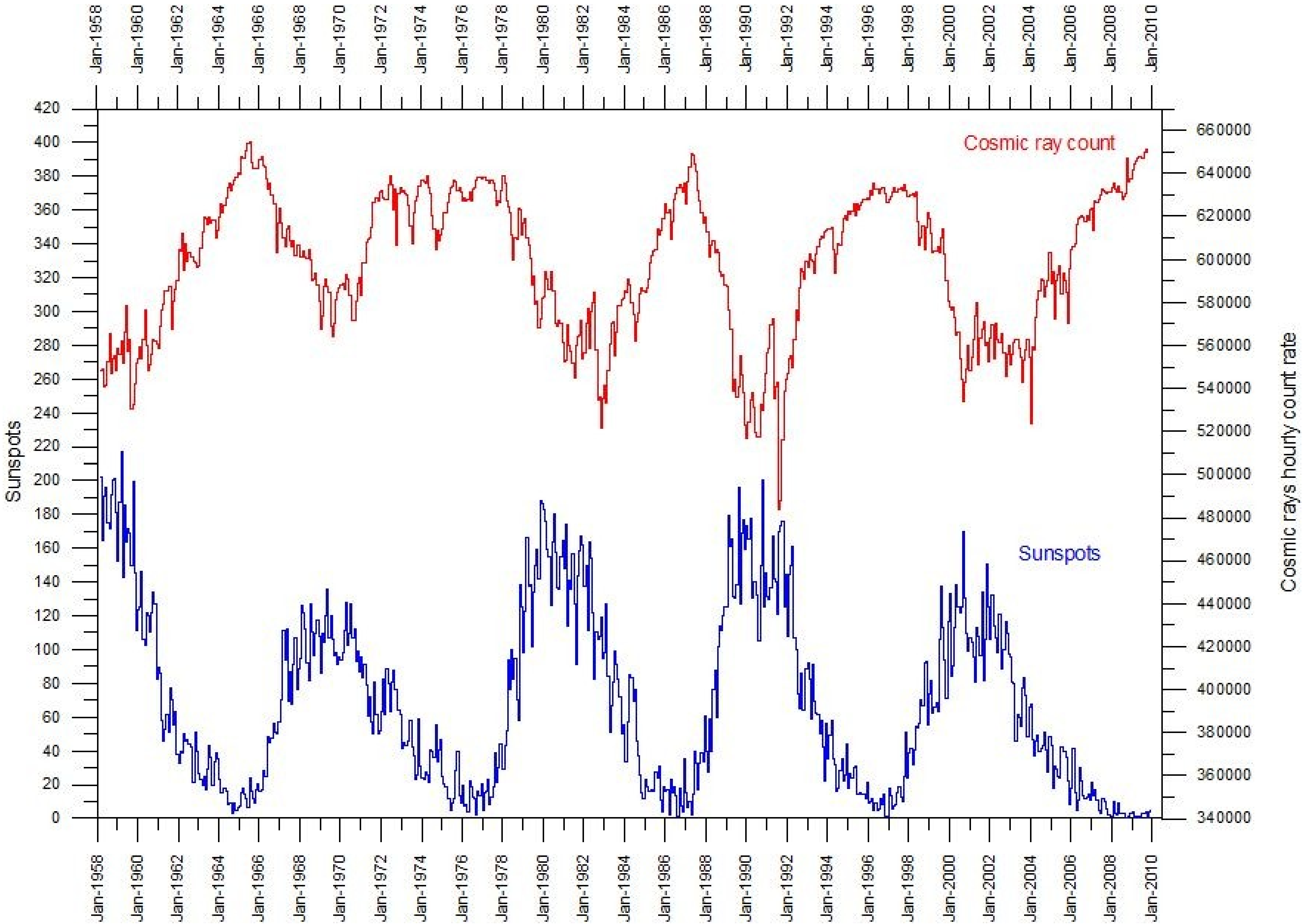
2010
2020


Cosmic ray count
Sunspots
Sunspots
Cosmic rays hourly count rate
Jan-1958
Jan-1960
Jan-1962
Jan-1964
Jan-1966
Jan-1968
Jan-1970
Jan-1972
Jan-1974
Jan-1976
Jan-1978
Jan-1980
Jan-1982
Jan-1984
Jan-1986
Jan-1988
Jan-1990
Jan-1992
Jan-1994
Jan-1996
Jan-1998
Jan-2000
Jan-2002
Jan-2004
Jan-2006
Jan-2008
Jan-2010
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
340000
360000
380000
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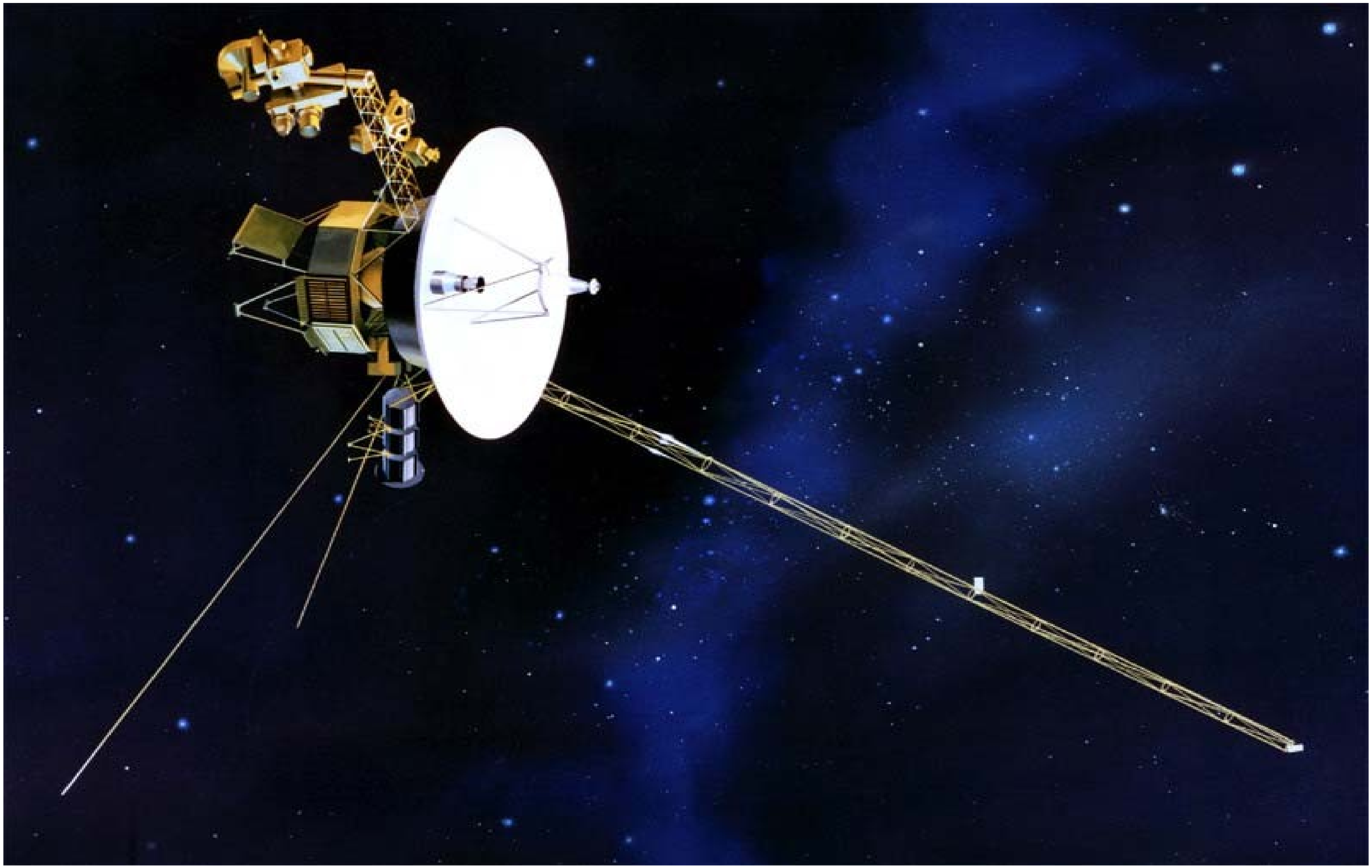
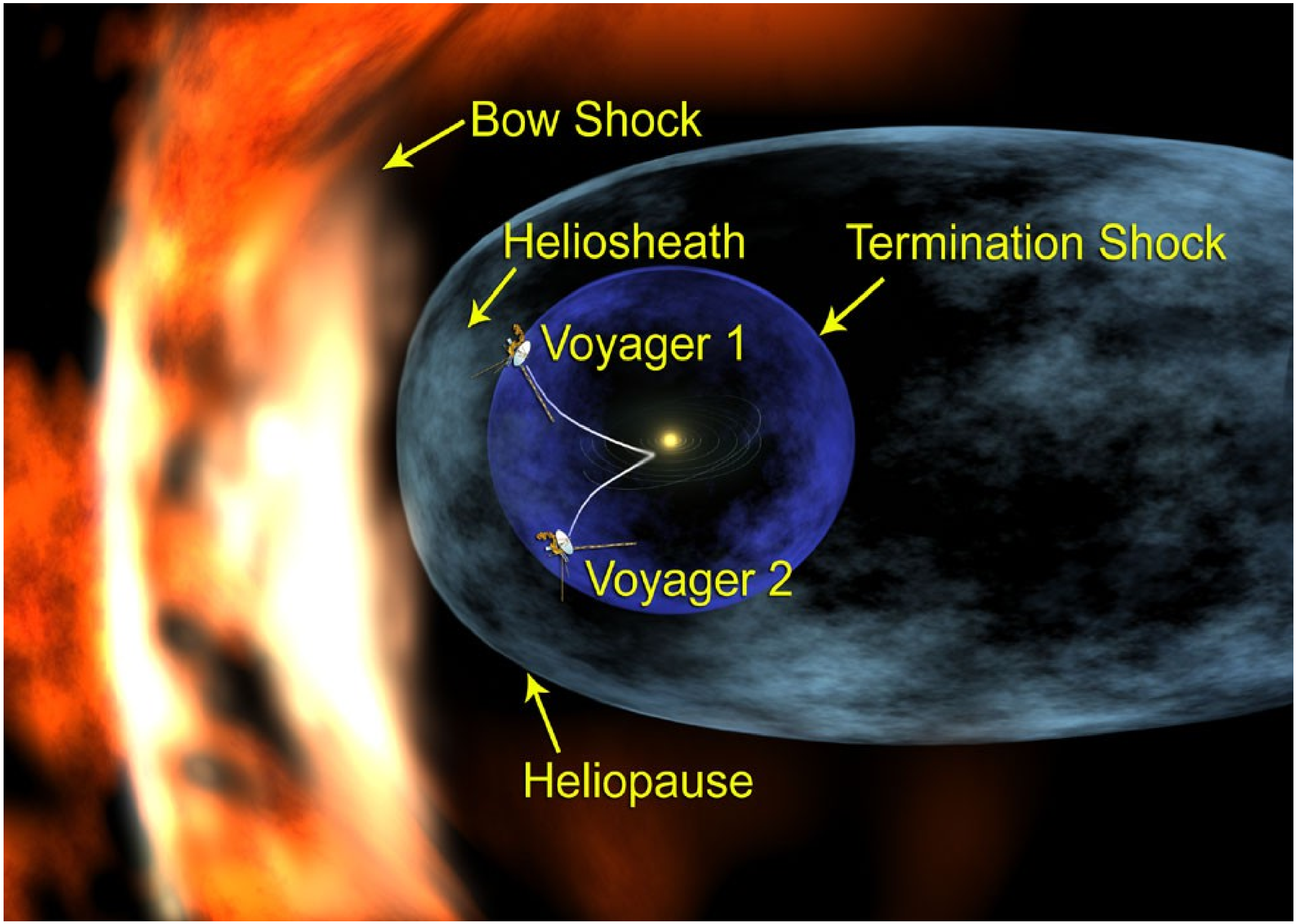
640000
660000

Voyager space craft



Powered by the heat from Pu-238 since the 1977

Current positions outside solar system



Artist drawing from NASA 2013

Deflection of cosmic ray particles