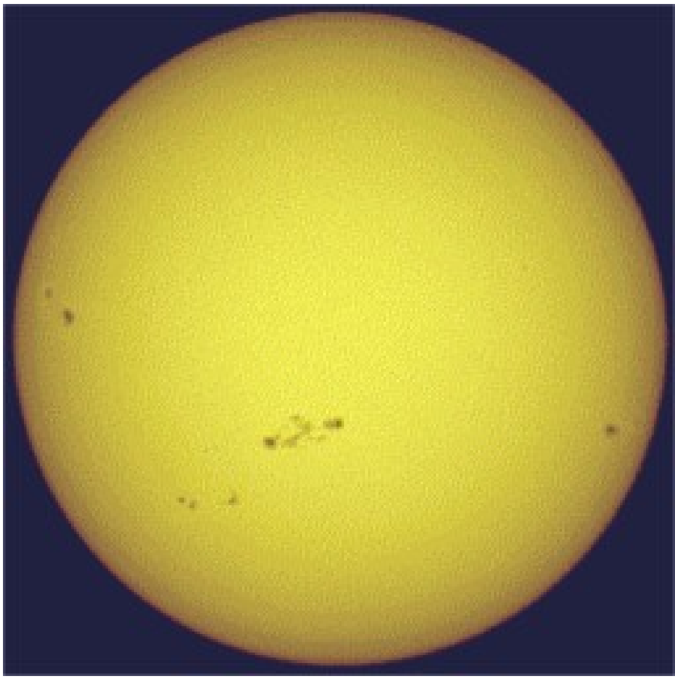
CAPITOLO 2

- **Solar wind**
- **Magnetic field of the sun**
- **Interplanetary magnetic field**

The Sun

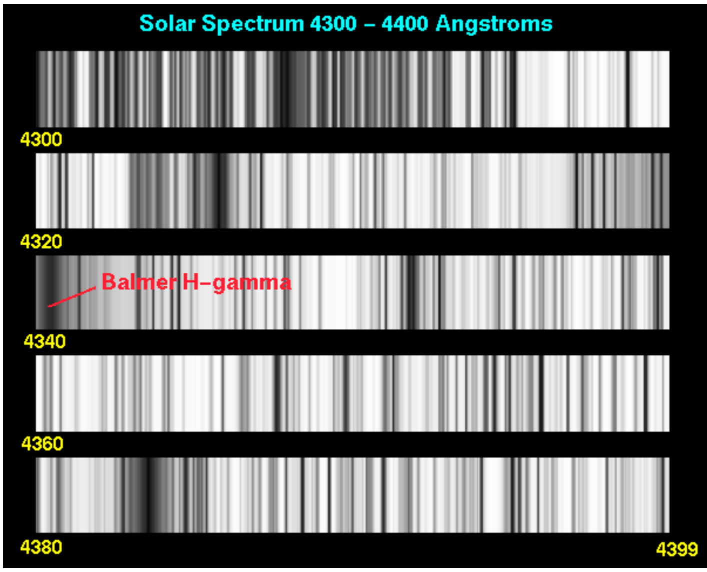
Physical properties:

- **Mass = 1.989 x 10^{30} kg**
- **Radius = 6.95 x 10^{8} m**
- **Mean Density = 1410 kg/m^3**
- **Rotation period: 25 days at equator, 36 at poles.**
- **Rotation axis inclined by 7.25 degree respect to the ecliptic (Earth orbital plane)**

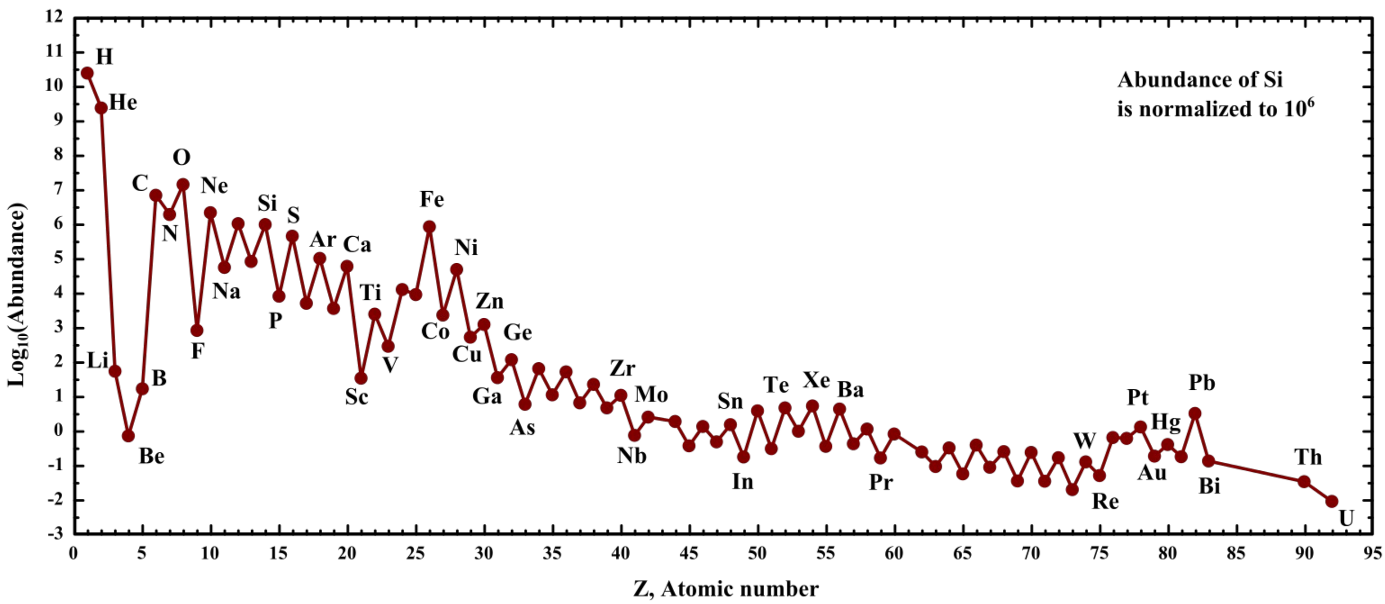


Composition (from spectral properties)

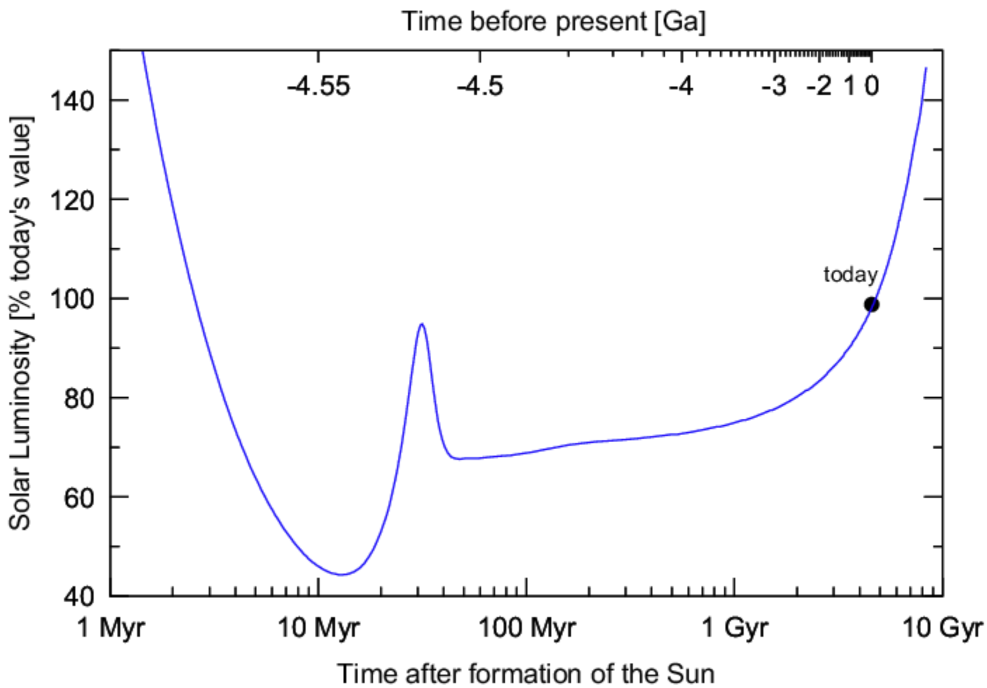
	% in mass	% in atom n.
H	73.4%	92.0%
He	25.0%	7.8%
O	0.8%	0.06%
C	0.2%	0.02%
N	0.09%	0.008%
Si	0.09%	0.004%
Mg	0.06%	0.003%
Ne	0.16%	0.010%
Fe	0.14%	0.003%
S	0.05%	0.002%



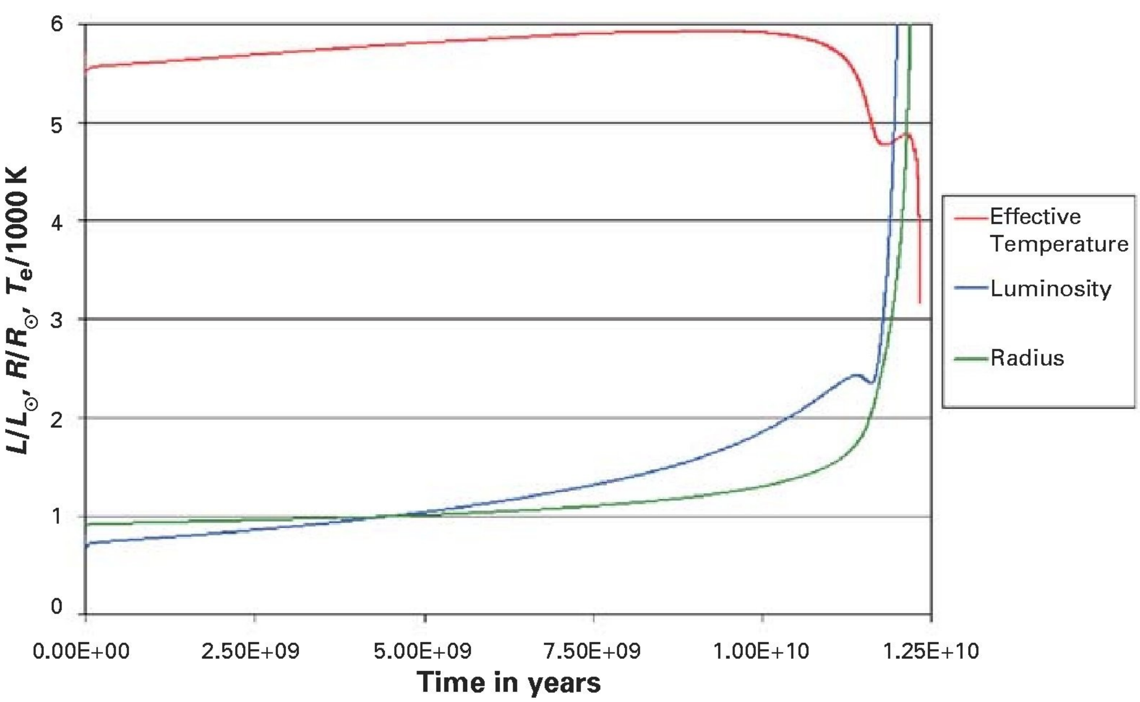
Abundance of chemical elements in the solar system created by early stellar nucleosynthesis and supernovae.



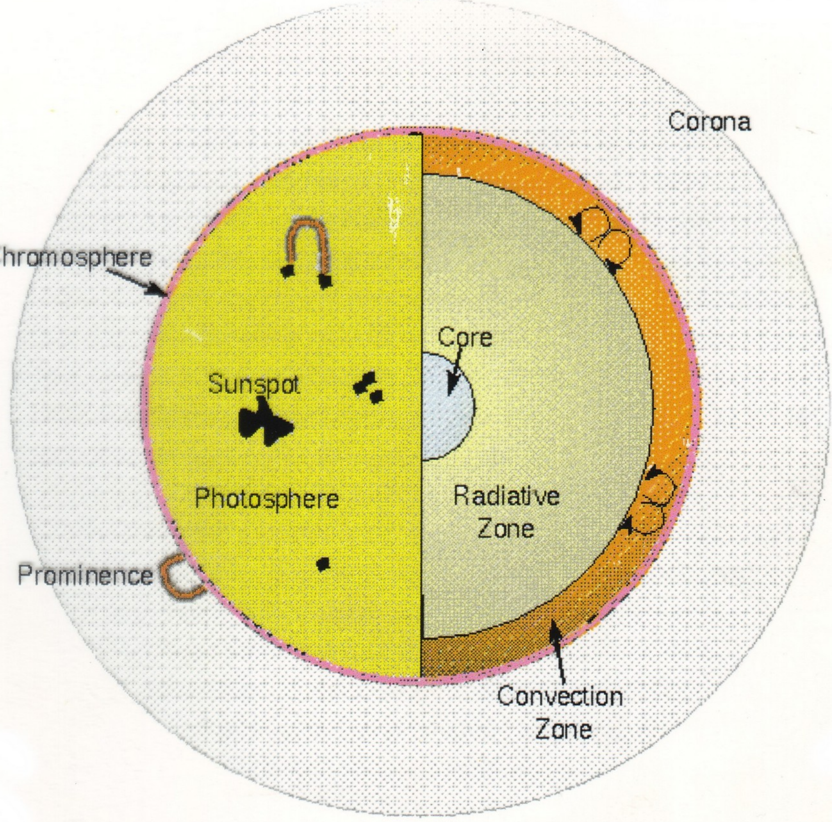
The sun evolves with time in luminosity



From stellar evolution models of Baraffe et al. 2015). The black dot is the presente sun. There are corresponding changes in radius and temperature.



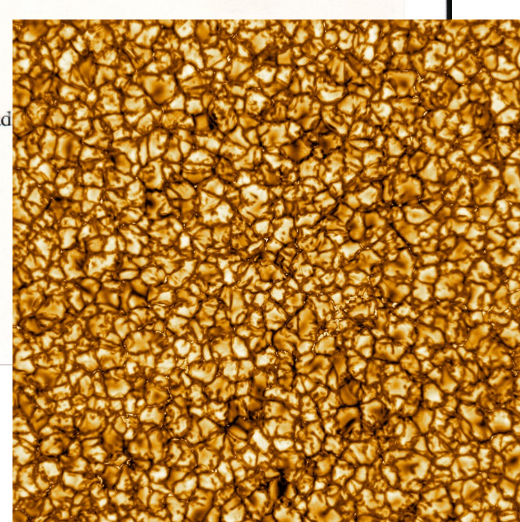
Solar spots; local magnetic activity perturbs convective motions and lowers the superficial temperature. The spot appears black.

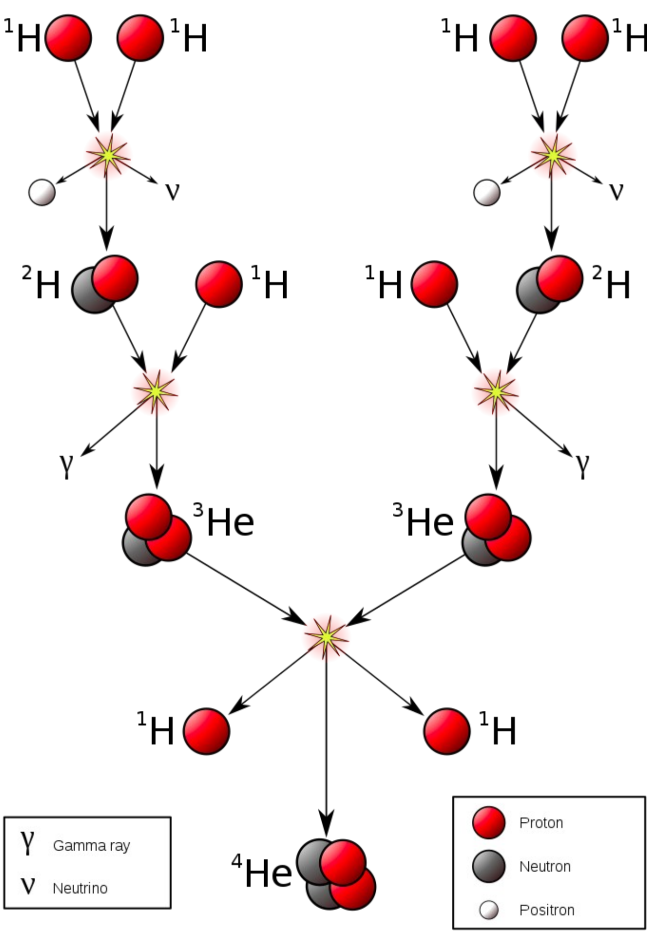


Energy is generated in the **core** where the temperature reaches 16 million K and the density is 160 g/cm^3 and then transported outward by radiation. In the **convection zone** rising and falling gas is used to tranfer the energy to the **photosphere** (''surface'' of the Sun). **Sunspots** are cooler, dimmer regions with strong magnetic fields. Some sunspots have **prominences** forming over them. The **chromosphere** is a thin pink layer above the photosphere that is hotter than the photosphere. The temperature increases outward into the **corona**, the very hot (1–2 million K) but tenuous atmosphere of the sun. Fast moving ions in the corona escape the Sun to form the **solar wind.**

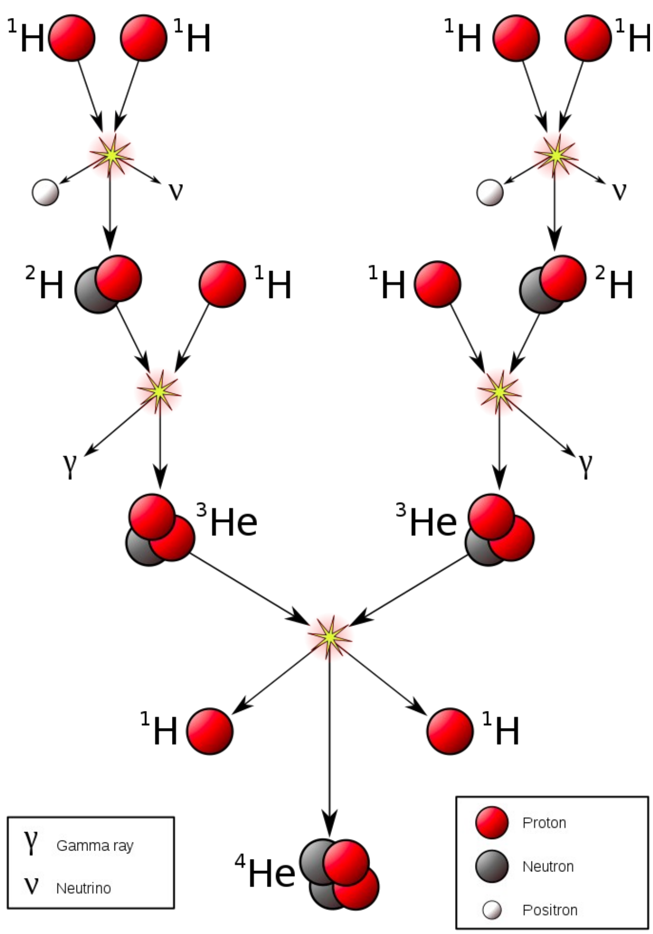
Figure 1:
Diametro = 1,392,000 km (109 diametri terrestri)
Mass = 333,000 Massa della Terra (1.99×10^{33} gr)
Composizione = 94% H_2 6% He 0.13% Elementi più pesanti
Temperatura Fotosfera = 5840 K
Temperatura Corona = 3.6 M K
Periodo di rotazione = 25 giorni (Equatore) 26.5 (30 gradi) 30 (60 grad

Sun granular surface with convective cells ~ 1000 km in size (Inouye solar telescope in Maui, Hawaii)





Proton-proton chain for the hydrogen fusion in the core of the sun. Minor contributions from the CNO chain.



Proton-proton chain for the hydrogen fusion in the core of the sun. Minor contributions from the CNO chain.

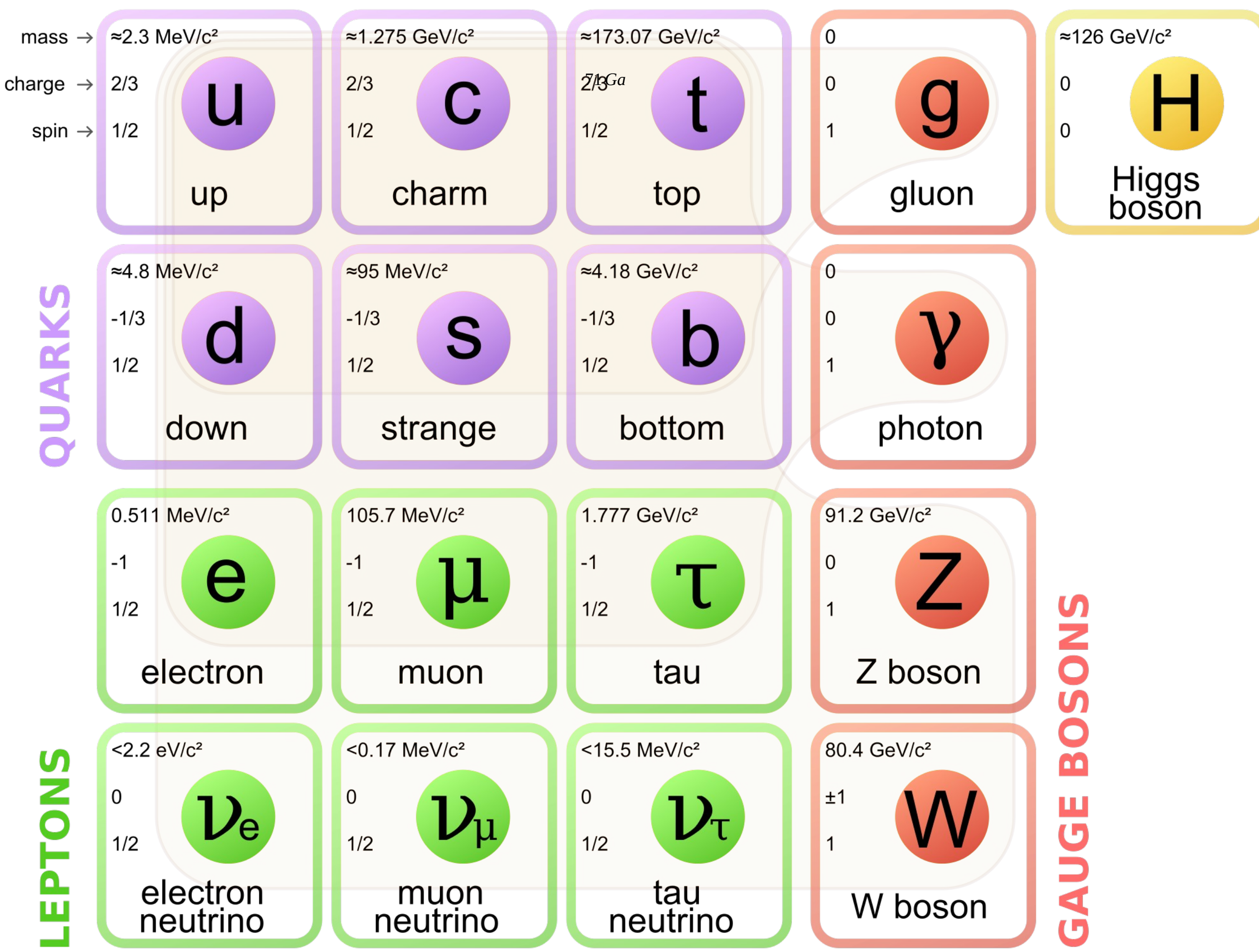
Solar neutrinos: the measurements of the neutrinos from the sun was too low, about 40% of the expected value. However, only the electron neutrinos were detected through the following reactions (for example GALLEX):

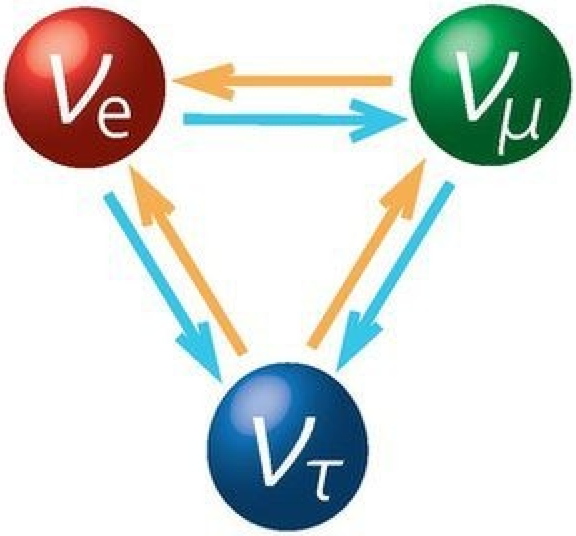
$$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$$

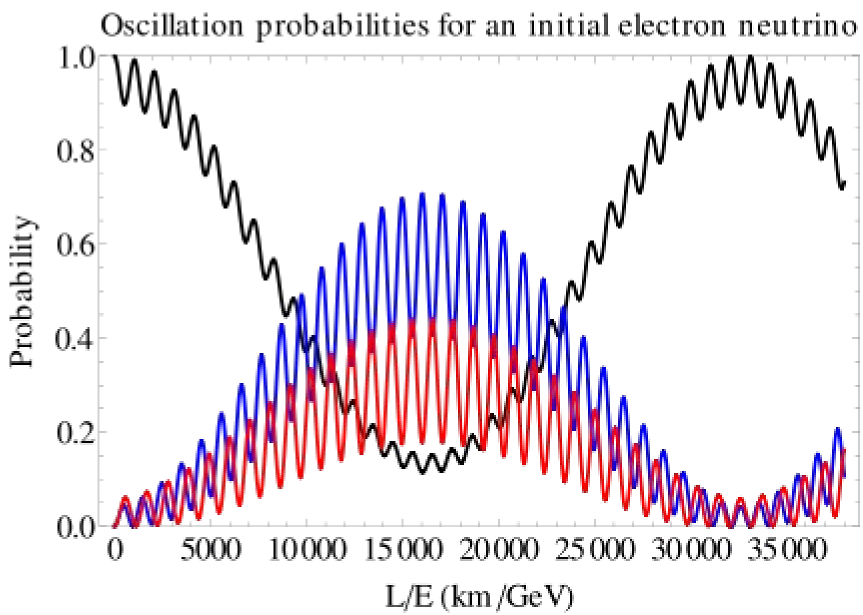
$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$$

$$n + \nu_e \rightarrow p + e^-$$

...BUT the neutrinos are of three different types….



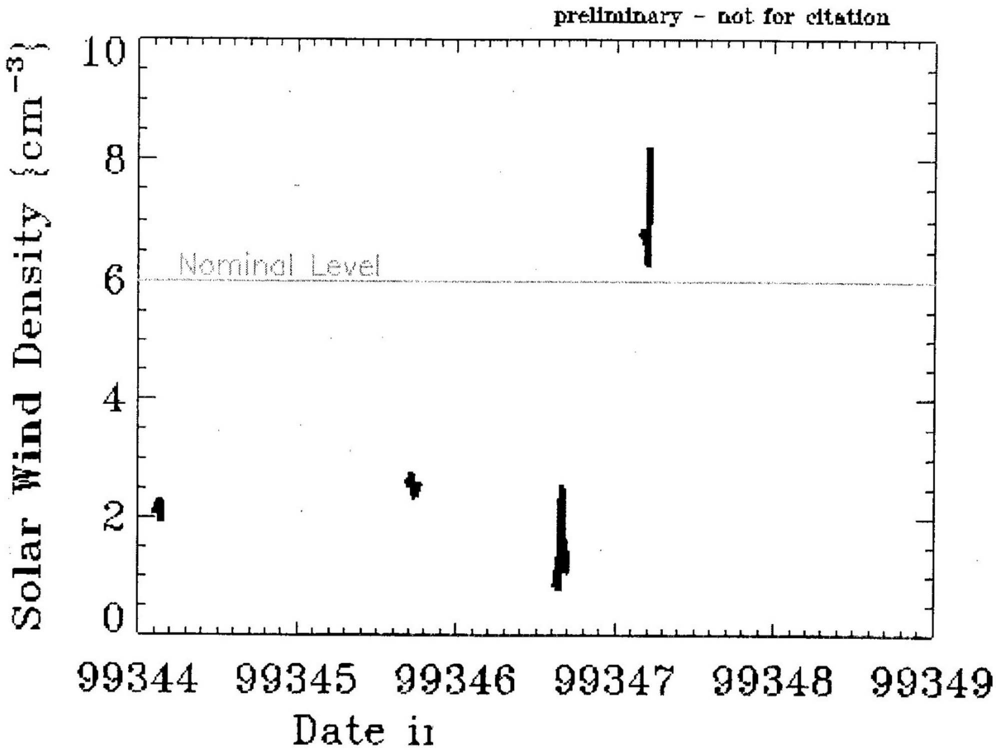


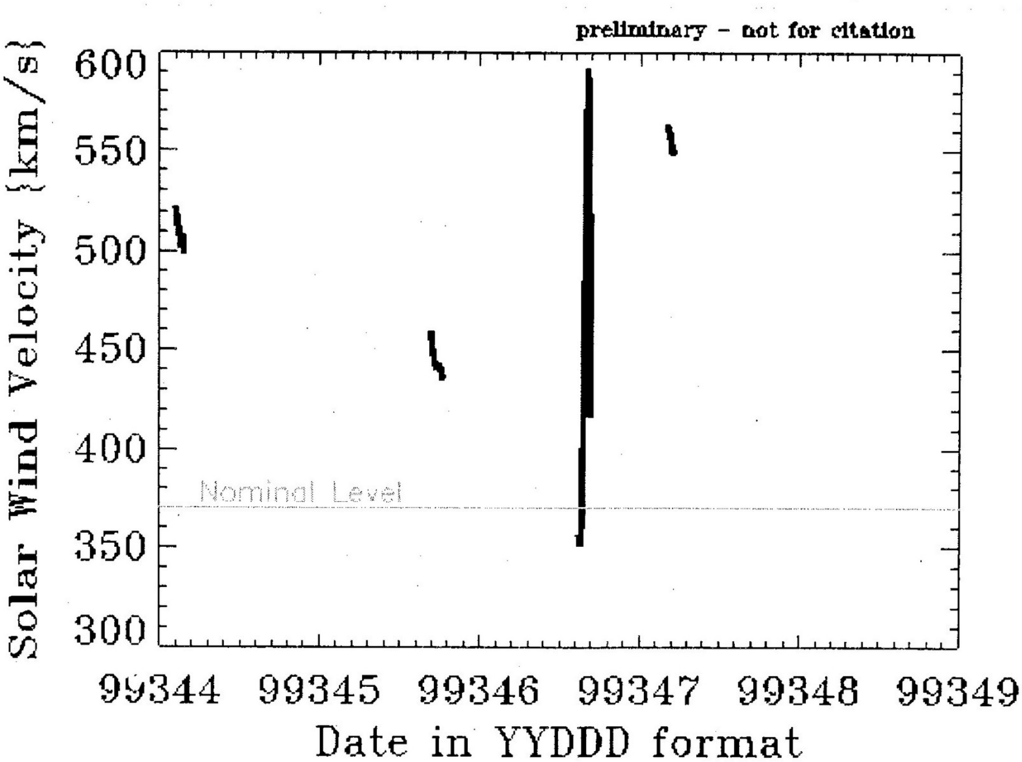


The black line shows the probability that a n_e remains of the same type. The blue line that it becomes a n_m, the red line that it becomes a n_t

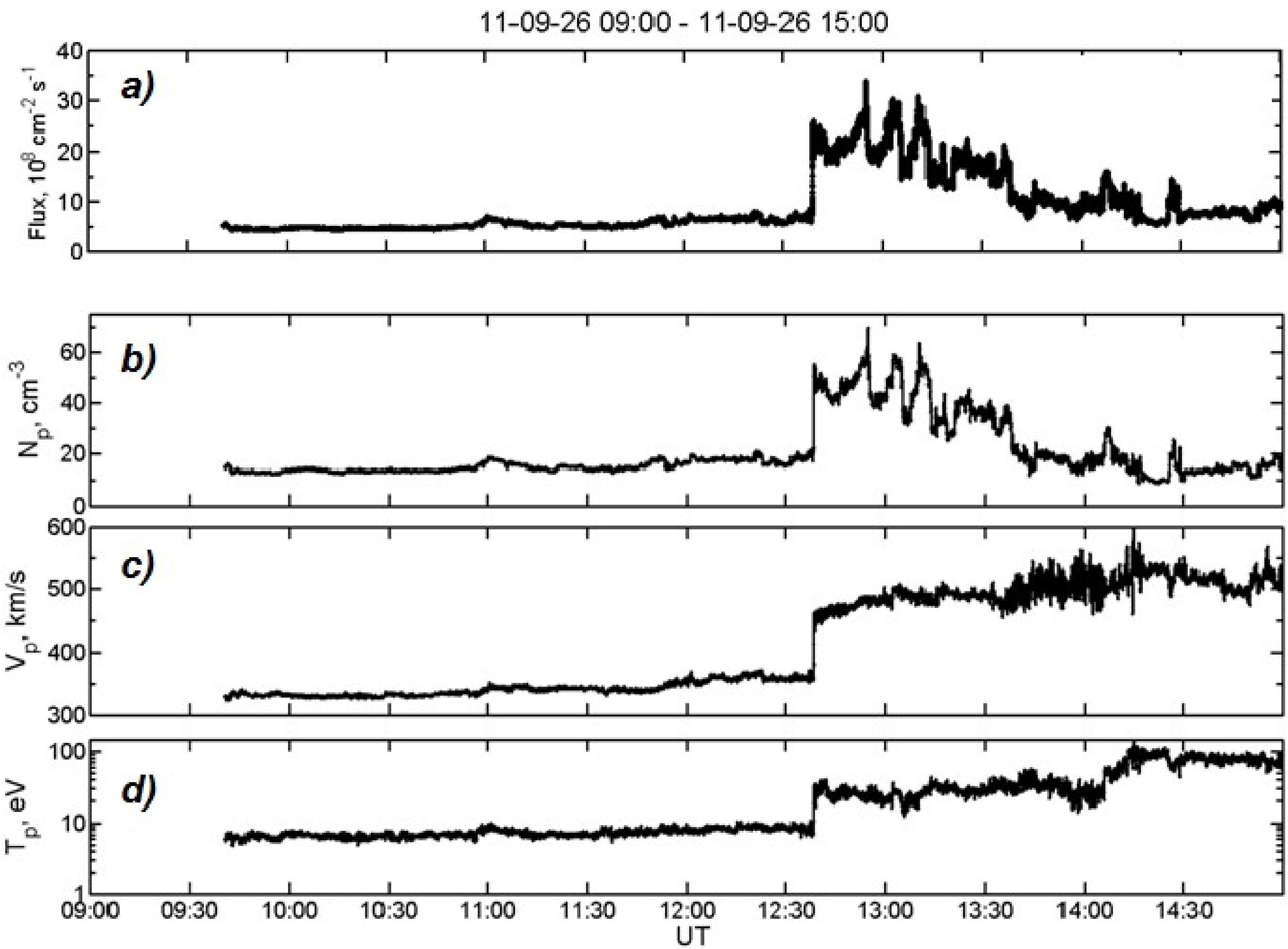
3) *Solar Wind Ion Density*

Long term variations of the solar wind.





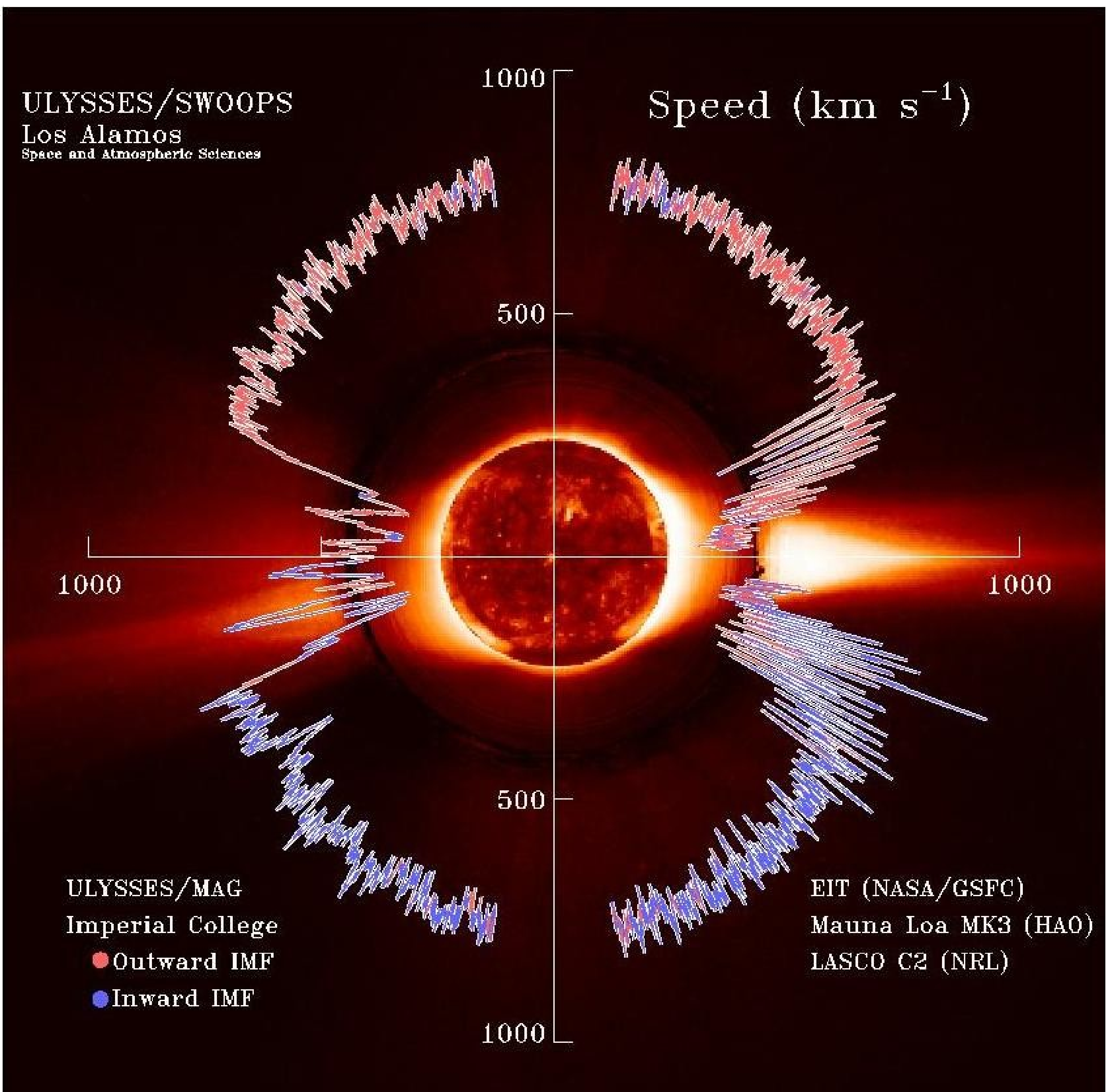
Short period variations due to turbulence and formation of shock waves.



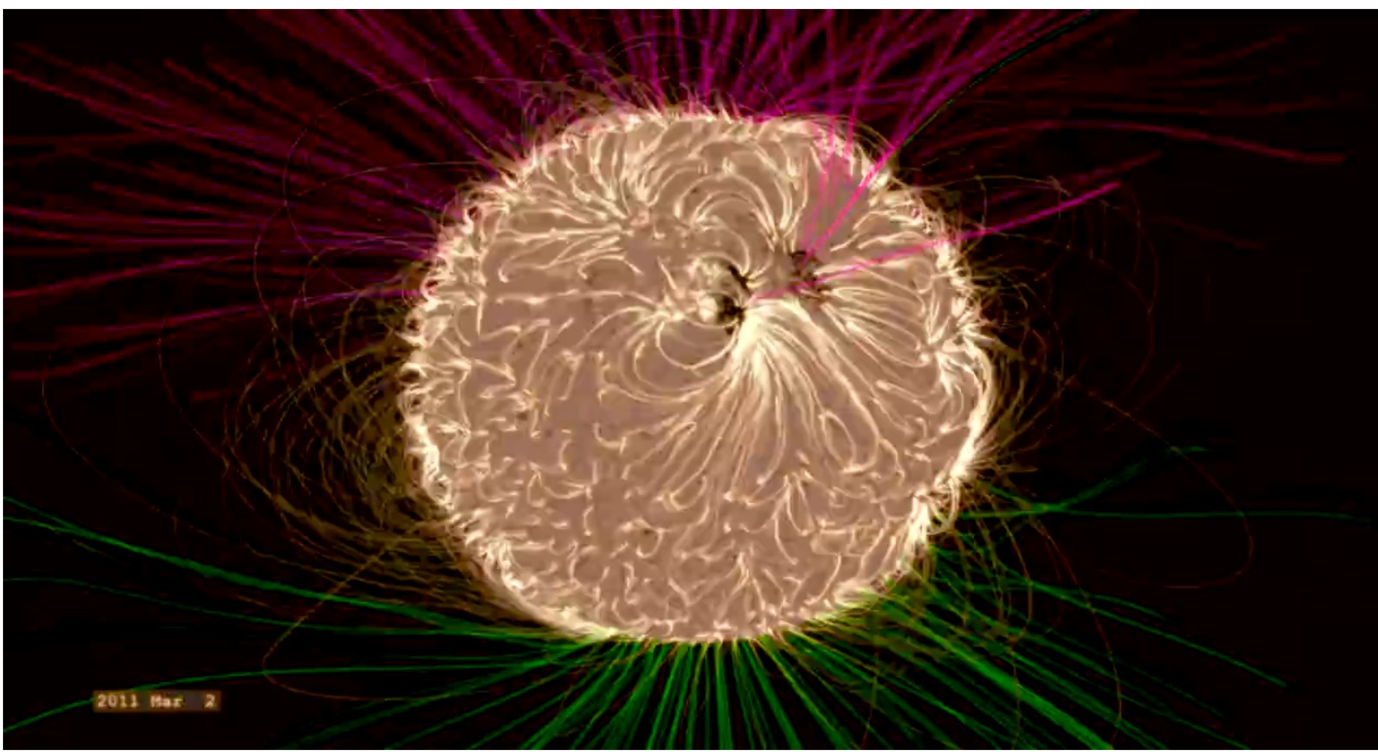
Solar wind:

- Bipolar: fast but thin
- Equatorial: slow but dense

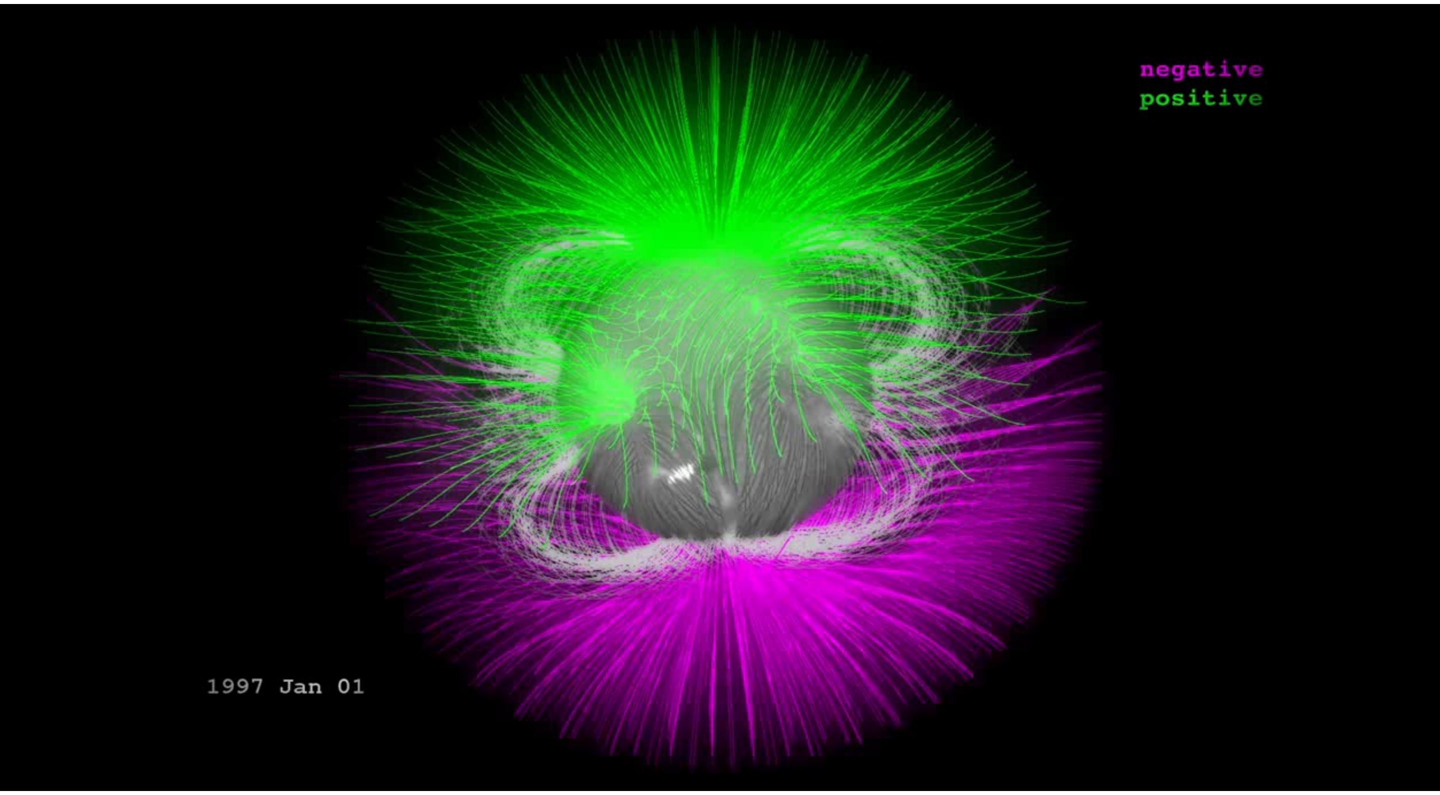
Data from Soho, Ulysses…

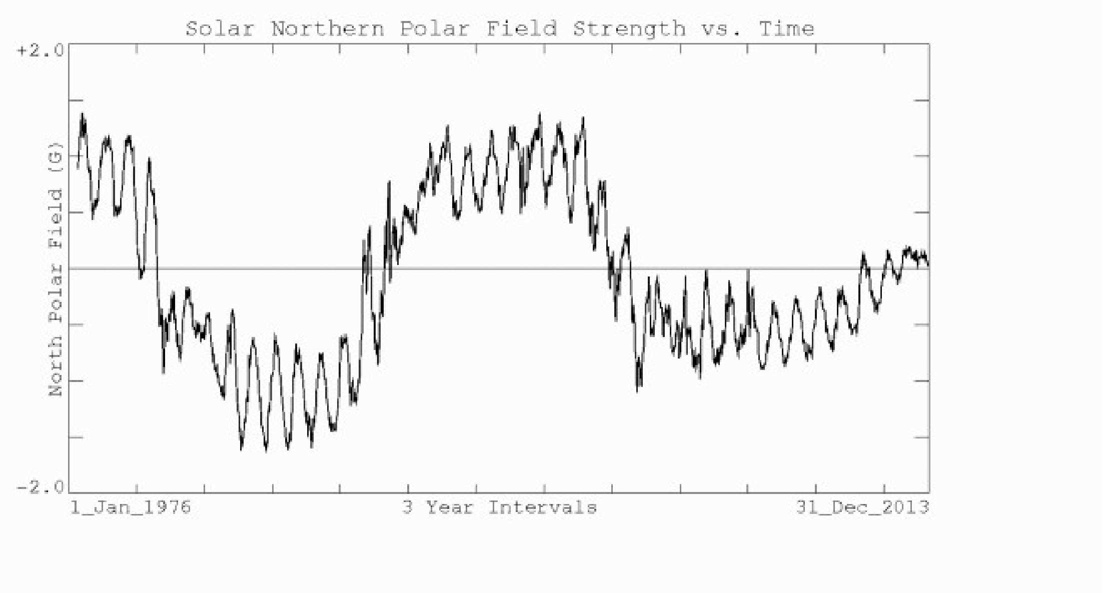


Animation of the solar magnetic field : white lines close within the solar plasma. Violet and green are the north and south lines of the bipolar filed. This field is dragged outwards by the solar wind.

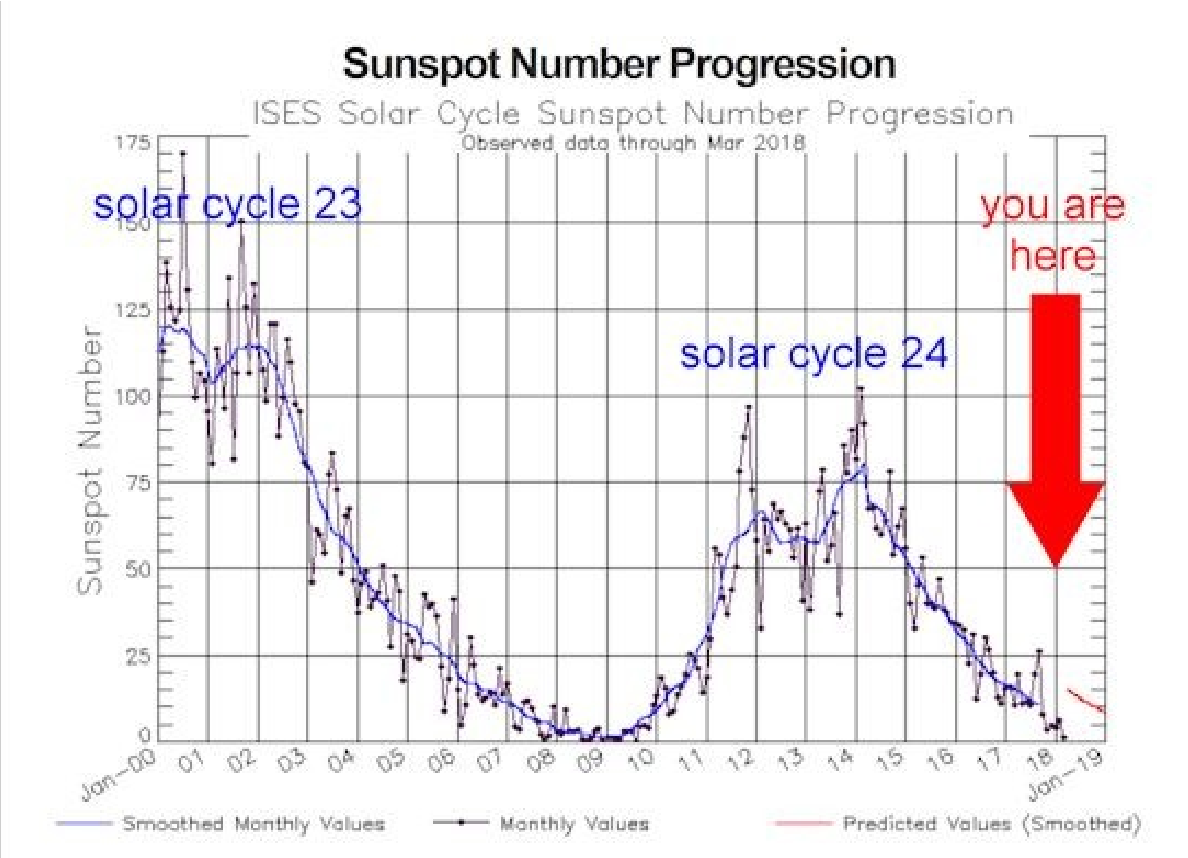


The solar cycle (Schwabe cycle). About every 11 years the field changes its polarity: field reversal.

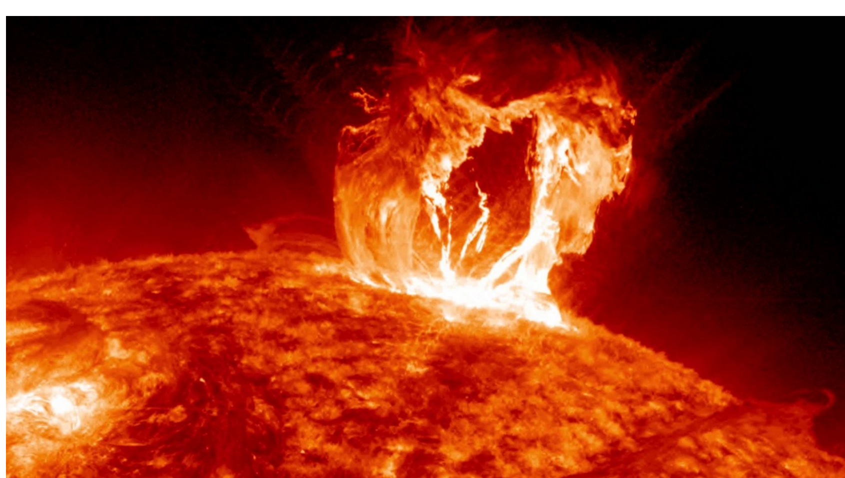


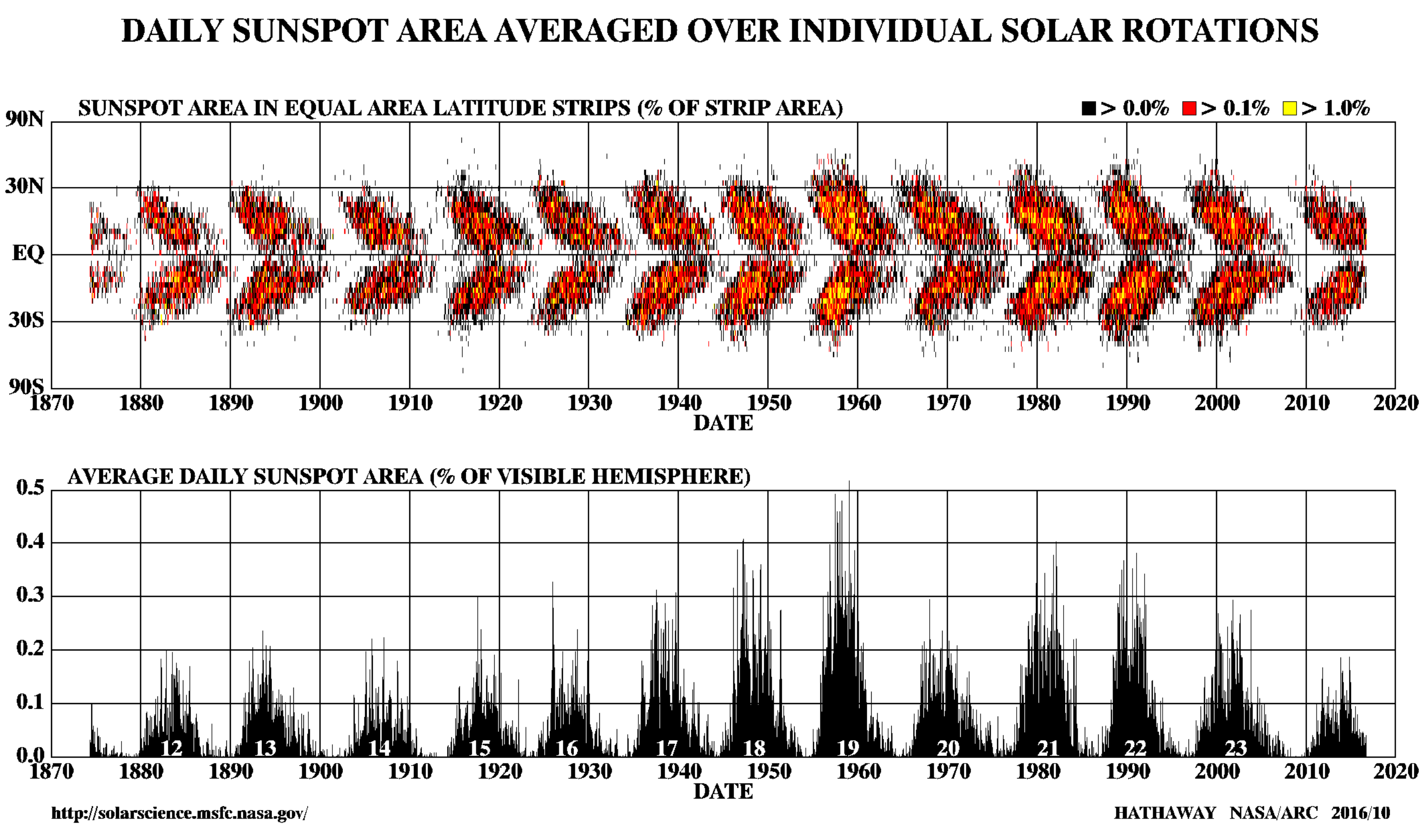


Solar cycle: increase in the magnetic activity of the sun and correspondent grow of the number of sunspots. At the solar maximum the spin flip occurs.

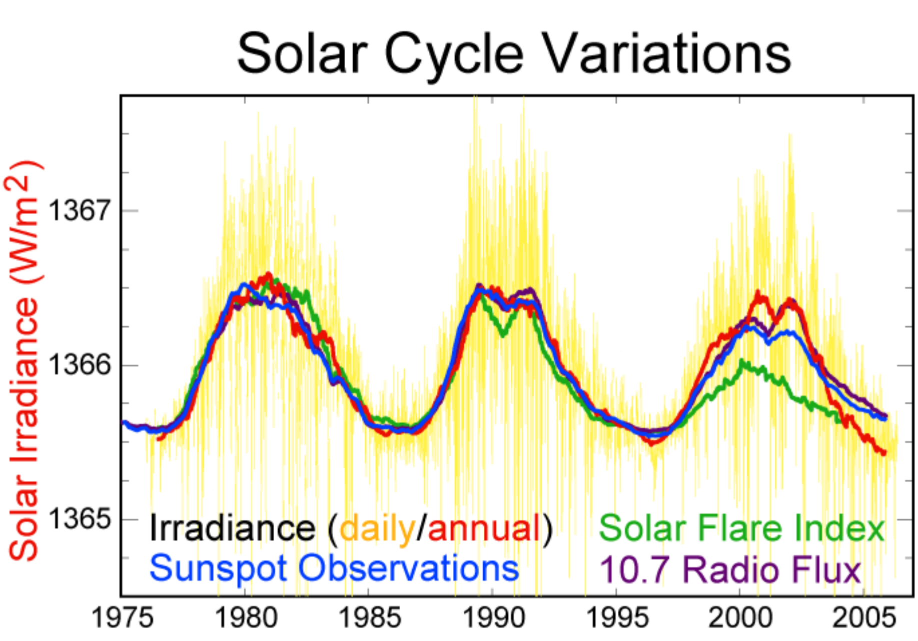


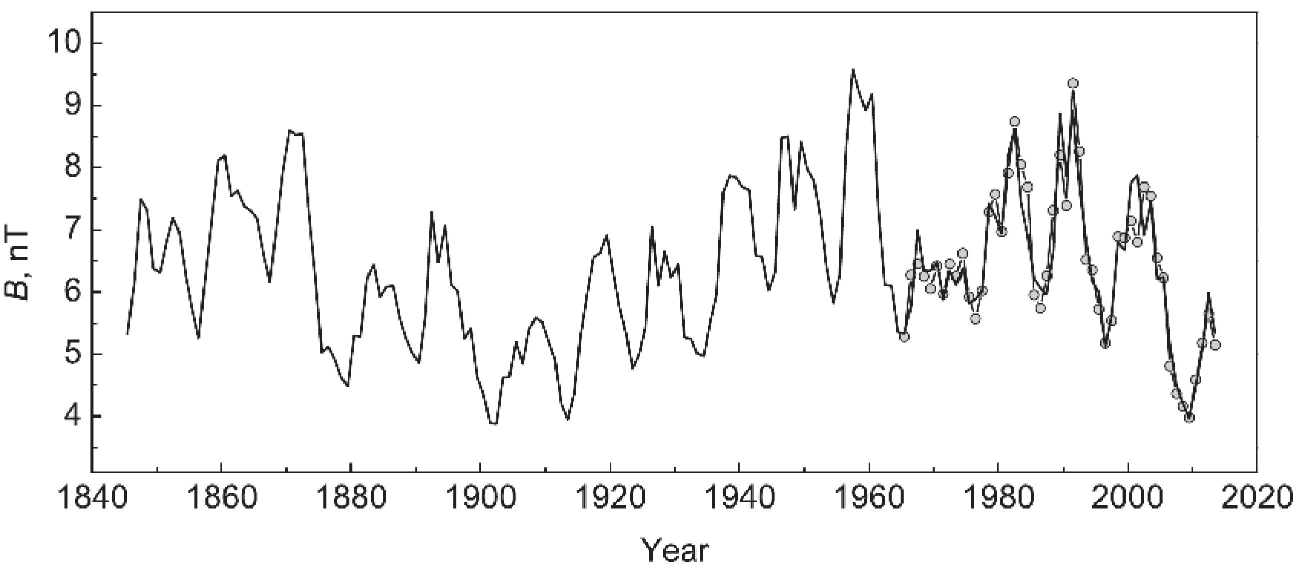
At solar maximum there is an increase in flares and coranal mass ejections.



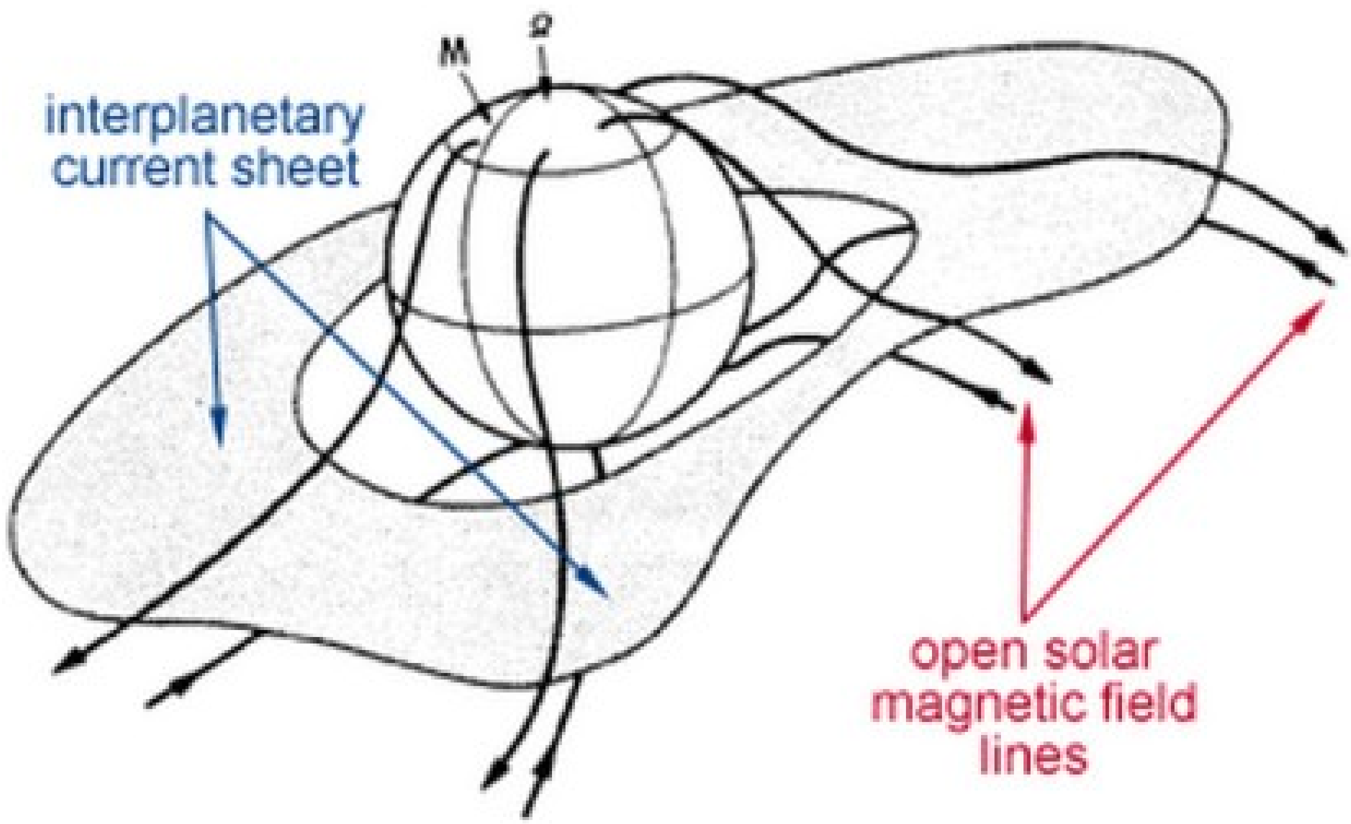


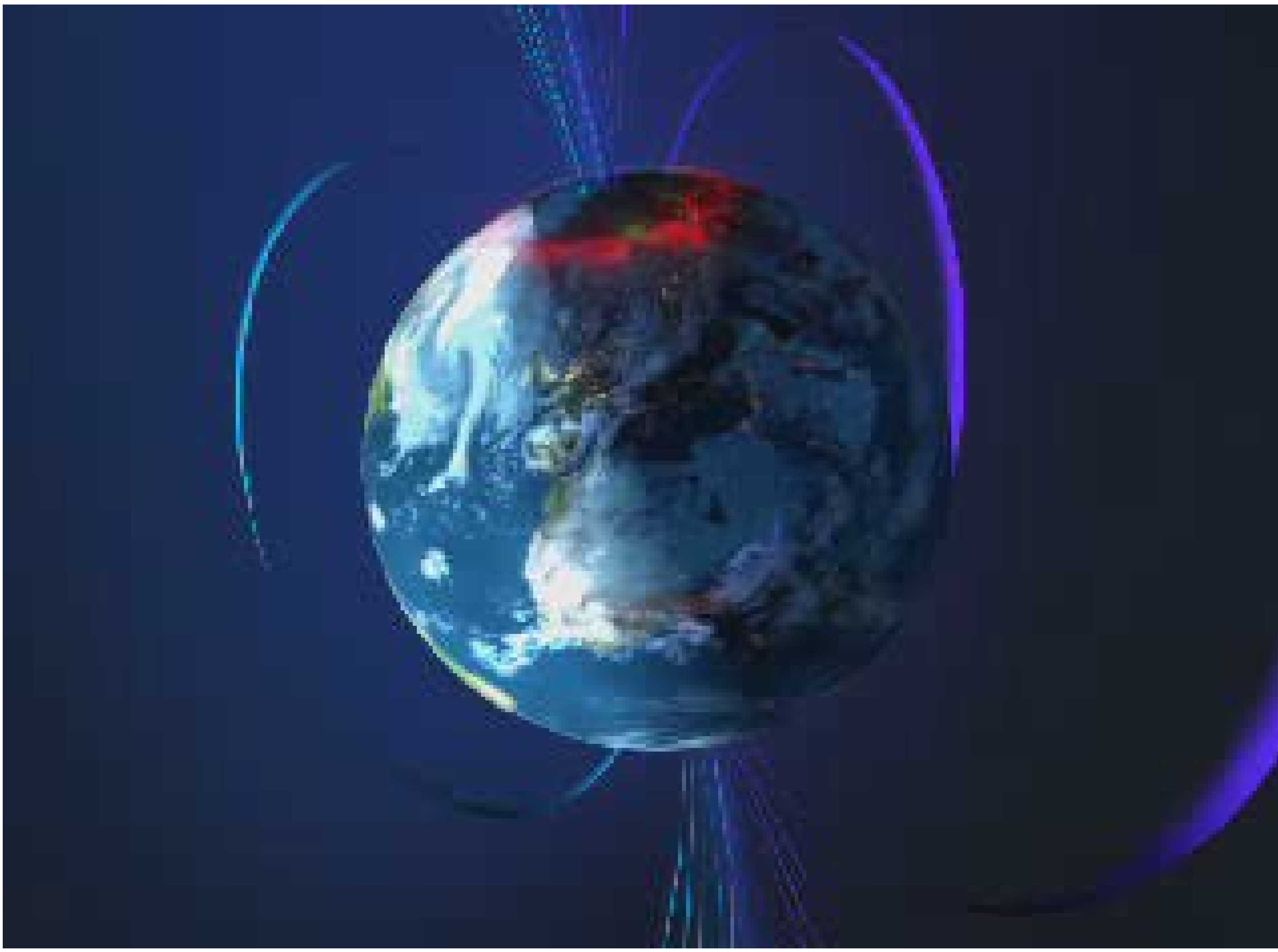
The periodicity of the sun. The butterfly diagram. Also the energy emitted by the sun is modulated.





IMF reconstructed back in time from observations
(Nagovitsyn and Osipova, MNRAS 492, 1914, (2019).





Solar wind and iterplanetary magnetic field

Solar wind: p^+, e^-

Physical parameters (at 1 au):

$$\rho \simeq 5-8 \ \ p/cm^3$$
$$v \simeq 300-500 \ \ km/s$$
$$T_e \simeq 10^5 \ \ K$$

The magnetic field lines are dragged away from the sun by the solar wind (MHD, Alfven theorem)

Computation of the magnetic field lines:

In a rotating reference frame centered on the sun and rotating with its rotation rate, the velocity components of the solar wind cells departing from the sun (radial direction) are:

$$u_r = u$$
$$u_\theta = 0$$
$$u_\phi = -\Omega r \sin\theta$$

The velocity vector in spherical coordinates is :

$$\boldsymbol{v} = \dot{r}\,\boldsymbol{e}_r + r\,\dot{\theta}\,\boldsymbol{e}_\theta + r\sin\theta\,\dot{\phi}\,\boldsymbol{e}_\phi$$

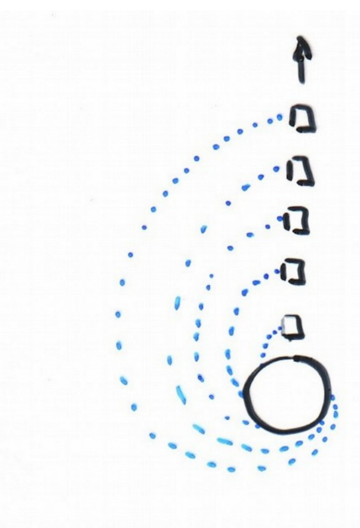
$$\frac{\dot{r}}{r\sin\theta\dot{\phi}} = \frac{dr}{dt}\frac{dt}{d\phi}\frac{1}{r\sin\theta} = \frac{dr}{d\phi}\frac{1}{r\sin\theta}$$

$$\frac{u_r}{u_\phi} = -\frac{u}{\Omega r \sin\theta} = \frac{dr}{d\phi}\frac{1}{r\sin\theta} \Rightarrow \quad \frac{dr}{d\phi} = -\frac{u}{\Omega}$$

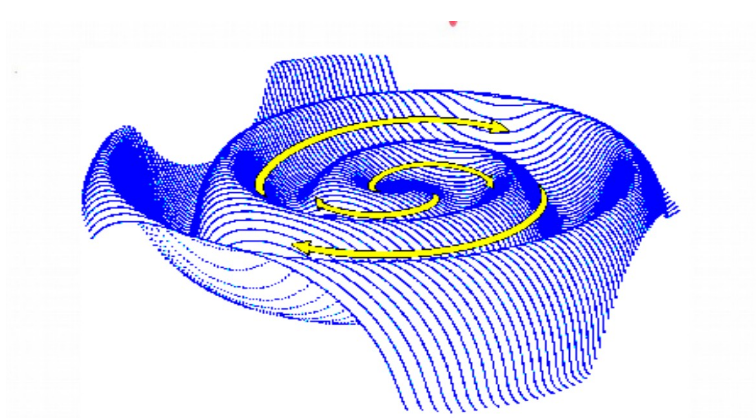
U is the expansion velocity of the solar wind. The equation of the trajectory is then an Archimede's spiral:

$$r - r_0 = -\frac{u}{\Omega}(\phi - \phi_0)$$

In the inertial reference frame the field lines coincide with the trajectory of the plasma cell in the rotating frame.



The magnetic field lines stick to the plasma cells as they move radially away from the sun.



We know the magnetic field lines, we have to compute the corresponding magnetic field vector. It must fulfil the following conditions:

$$\boxed{\begin{aligned} & r - r_0 = -\frac{u}{\Omega}(\phi - \phi_0) \\ & \nabla \cdot \boldsymbol{B} = 0 \end{aligned}}$$

$$B_r = B_0 \left(\frac{r_0}{r}\right)^2$$

$$B_\theta = 0$$

$$B_\phi = -B_0 \frac{\Omega r_0}{u} \frac{r_0}{r} \sin\theta$$

$$\nabla \cdot \boldsymbol{B} = \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 B_r) + \frac{1}{r \sin\theta} \frac{\partial}{\partial \theta}(B_\theta \sin\theta) + \frac{1}{r \sin\theta} \frac{\partial B_\phi}{\partial \phi} = 0$$

Is the field tangent to the field lines? Let’s parametrize the field line as it were the trajectory of some particle.

$$r = at + r_0$$

$$\phi = -\frac{\Omega}{u} at + \phi_0$$

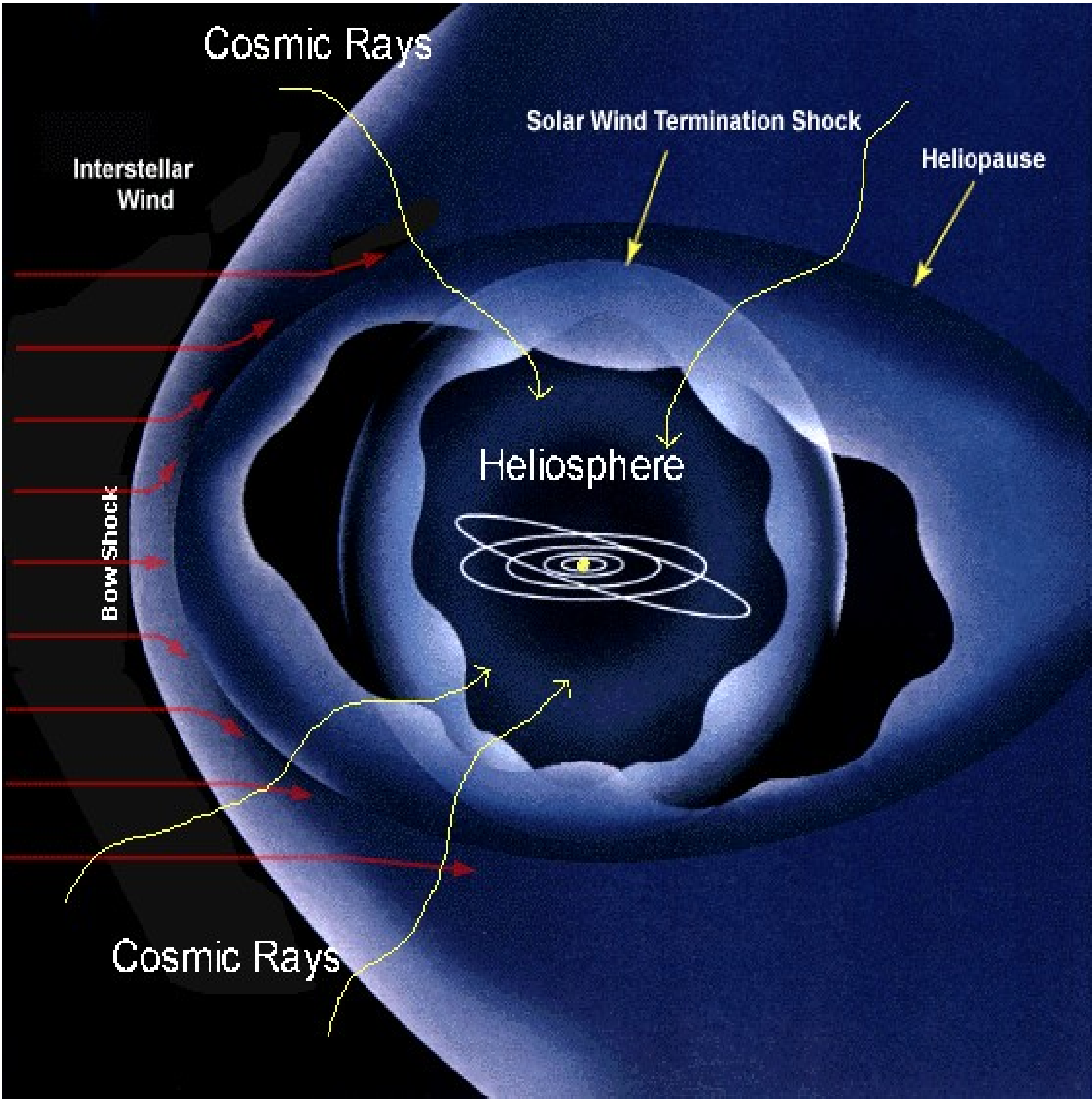
The tangent vector to this trajectory is (as usual) :

$$\boldsymbol{v} = \dot{r}\,\boldsymbol{e_r} + r\,\dot{\theta}\,\boldsymbol{e_\theta} + r\sin\theta\,\dot{\phi}\,\boldsymbol{e_\phi} = a\,\boldsymbol{e_r} + a\,r\sin\theta\left(-\frac{\Omega}{u}\right)\boldsymbol{e_\phi}$$

The ratio between the r and φ of the tangent vector is the same between the B_r and B_φ component of the magnetic field.

$$\frac{B_r}{B_\phi} = -B_0\frac{r_0^2}{r^2}\frac{u\,r}{B_0 r_0^2\Omega\sin\theta} = -\frac{u}{\Omega}\frac{1}{r\sin\theta} = \frac{v_r}{v_\phi}$$

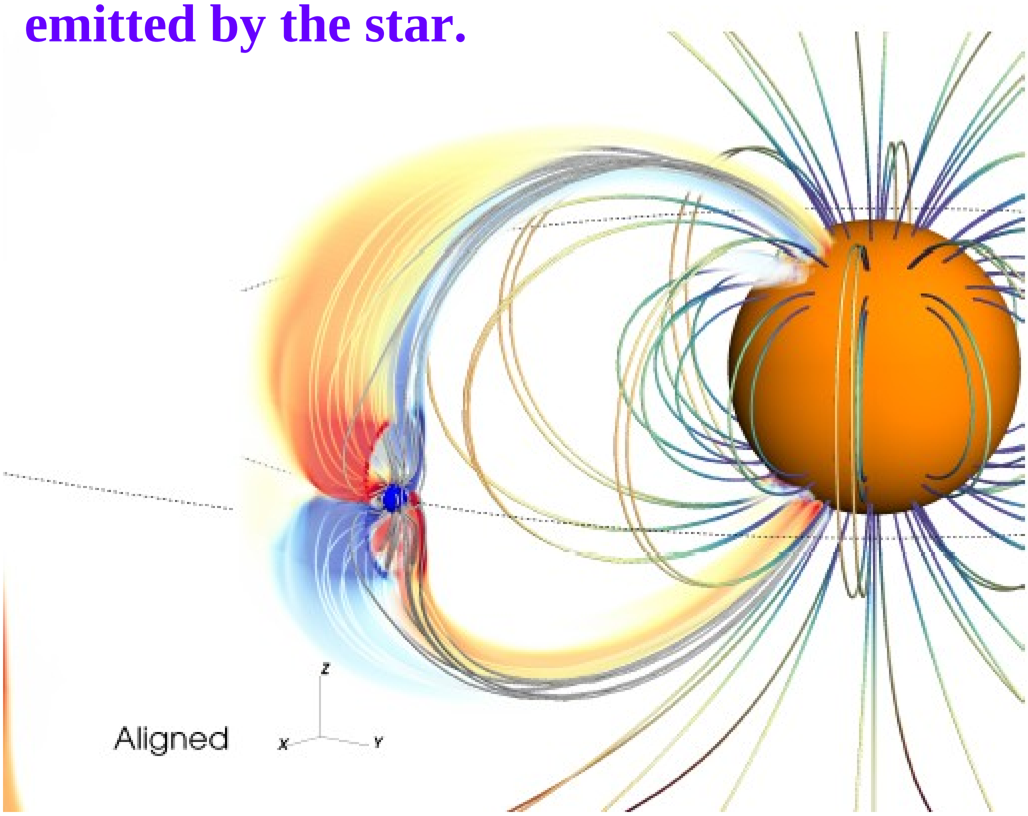
Vector B is tangent to the filed lines and its divergence is 0.



Limits of the magnetic field of the solar system (heliosphere) embedded in the galactic wind.

Alfven wings in hot Jupiters.

If the planet is very close to the star (Hot Jupiter), there is an exchange of magnetic energy between the planet and the star surface since the planet moves at high speed respect to the plasma (wind) emitted by the star.



Stugarek et al. (2015)

There is also an exchange of angular momentum possibly causing the migration of the planet and its heating.