Profile of $v_\varphi(r)$

$$v_\varphi B_r - v_r B_\varphi = \Omega r B_r$$

$$r v_\varphi - \frac{B_r}{4\pi\rho v_r} r B_\varphi = L$$

eliminate B_φ

$$v_\varphi = \Omega r \frac{\frac{L}{\Omega r^2} M_A^2 - 1}{M_A^2 - 1}$$

$$M_A \equiv \frac{v_r}{v_A},\quad v_A \equiv \frac{B_r}{\sqrt{4\pi\rho}}$$

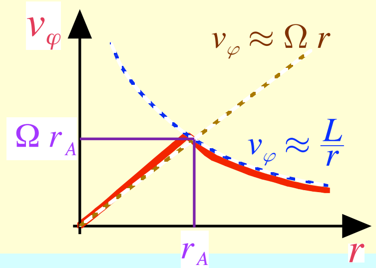
When $M_A = 1$ $(r = r_A \ldots$ *Alfvén critical point*$)$, the numerator should be zero:

$$\frac{L}{\Omega r^2} M_A^2 - 1 = 0 \;\Rightarrow\; L = \Omega r_A^2 = r_A (\Omega r_A)$$

This indicates that the Alfvén critical point rotates at the same rate as the solar equator (**rigid-body rotation**).

$$v_\varphi = \Omega r \frac{\left(\frac{r_A}{r}\right)^2 M_A^2 - 1}{M_A^2 - 1}$$

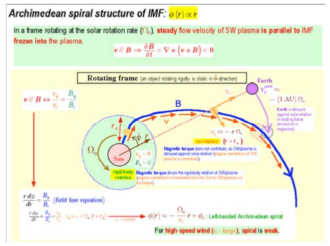
When $R_\odot \le r < r_A$ => $M_A \ll 1$, $v_\varphi \approx \Omega r$.
(**rigid-body rotation** via strong magnetic torque)

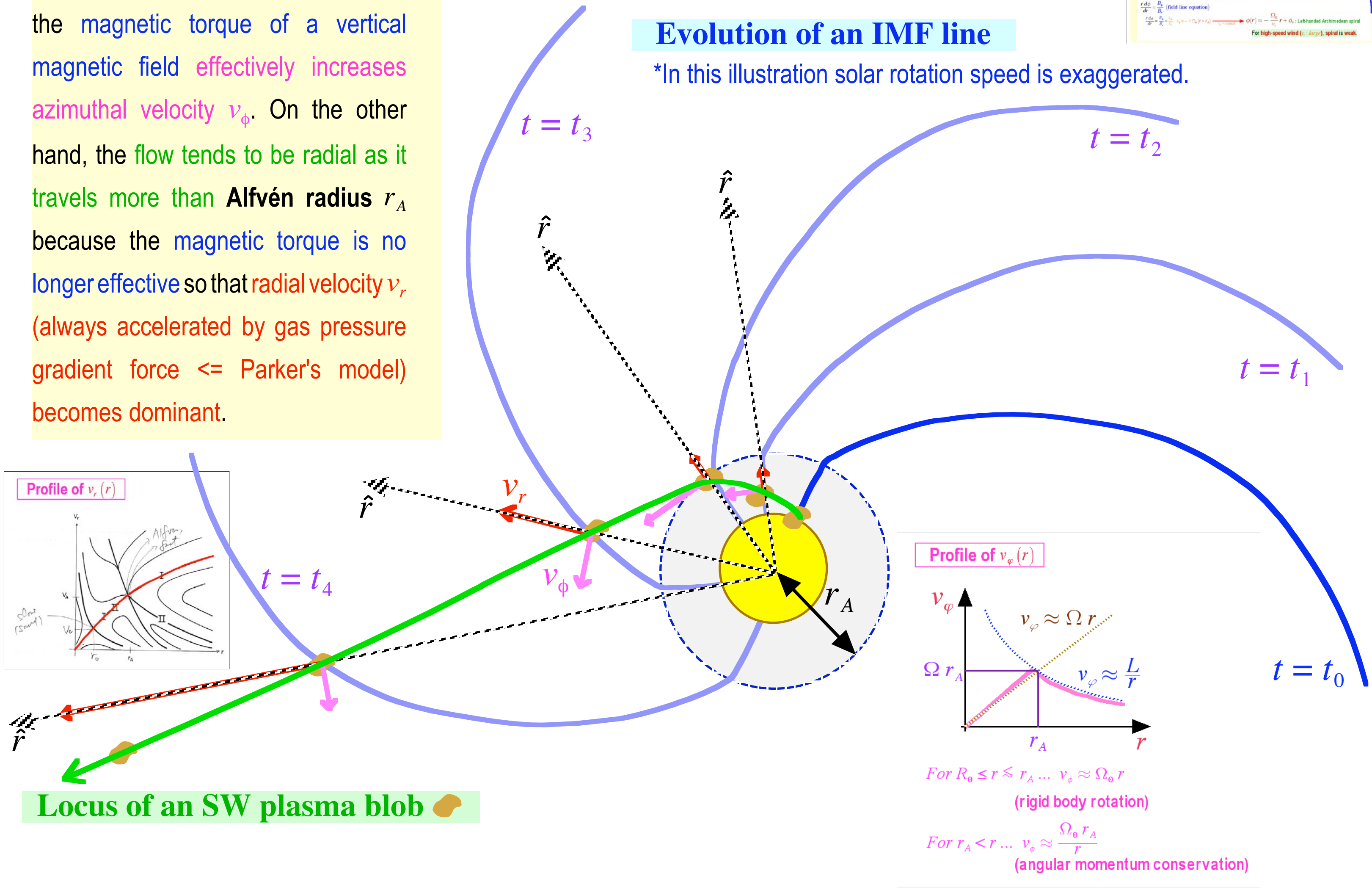


When $r_A < r$ => $M_A \gg 1$, $v_\varphi \approx \frac{L}{r}$.
(angular momentum per unit mass is almost conserved $J = v_\varphi r \sim L = const.$ because magnetic torque is weak, indicating that solar wind plasma with frozen-in IMF is delayed against the solar rotation => **spiral shape of the IMF**)

Solar wind in inertial frame...

Solar-wind flow initially tends to be tangential to the solar surface because the magnetic torque of a vertical magnetic field effectively increases azimuthal velocity v_ϕ. On the other hand, the flow tends to be radial as it travels more than **Alfvén radius** r_A because the magnetic torque is no longer effective so that radial velocity v_r (always accelerated by gas pressure gradient force <= Parker's model) becomes dominant.





2.5D version of WD model...

solid... field line
dotted... stream line

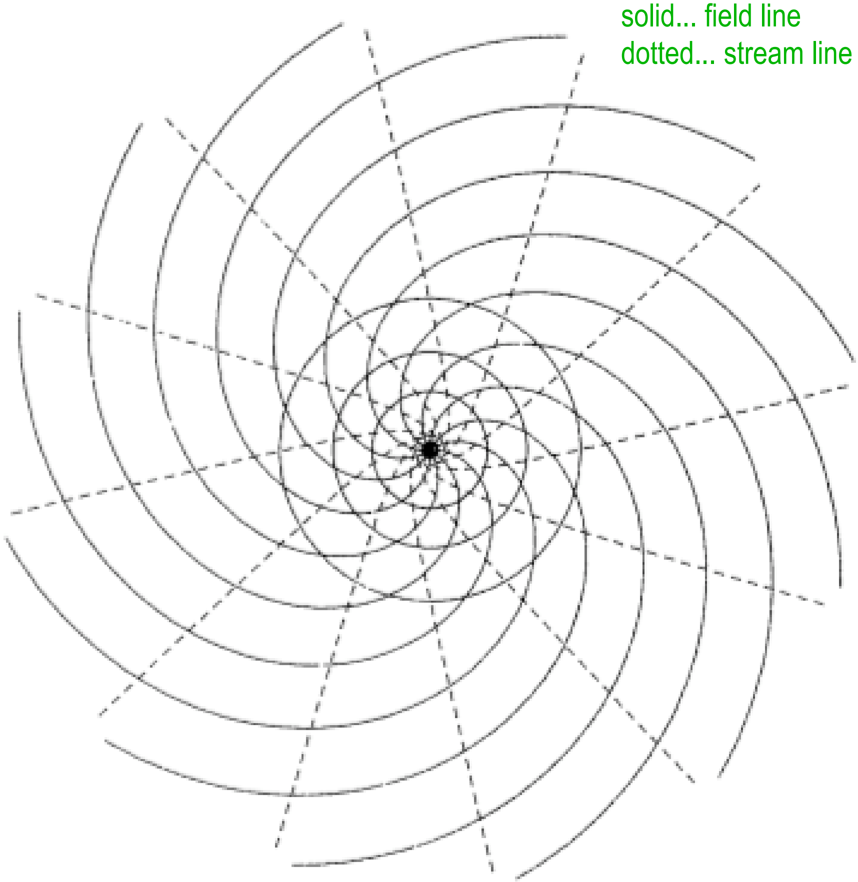


Fig. 4. Magnetic field lines (solid) and flow stream lines (dashed) in the equatorial plane ($0 \leqq r \leqq 4r_{A,WD}$). Three circles represent the location of the three critical surfaces shown in Fig. 3b

Sakurai (1985)

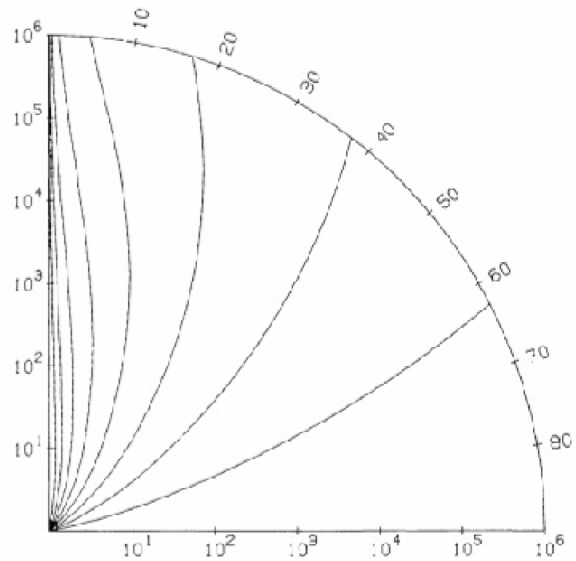


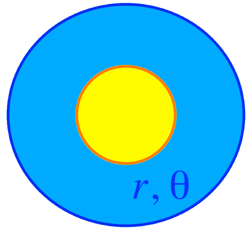
Fig. 6. The structure of the poloidal field at large distances, plotted in logarithmic scale in r. The flow is continuously deflected toward the rotation axis. At $r = 10^6 r_{A,WD}$, the field lines with $\theta_0 \leq 50°$ are bundled into a cone $\theta \leq 5°$

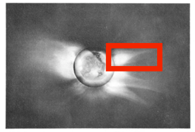
Pneuman-Kopp 2-dimensional model

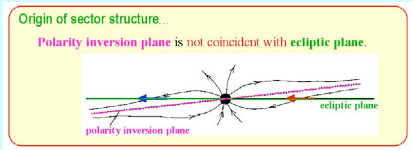
(depends on *r* & θ, *r & θ–components of a vector* are considered)

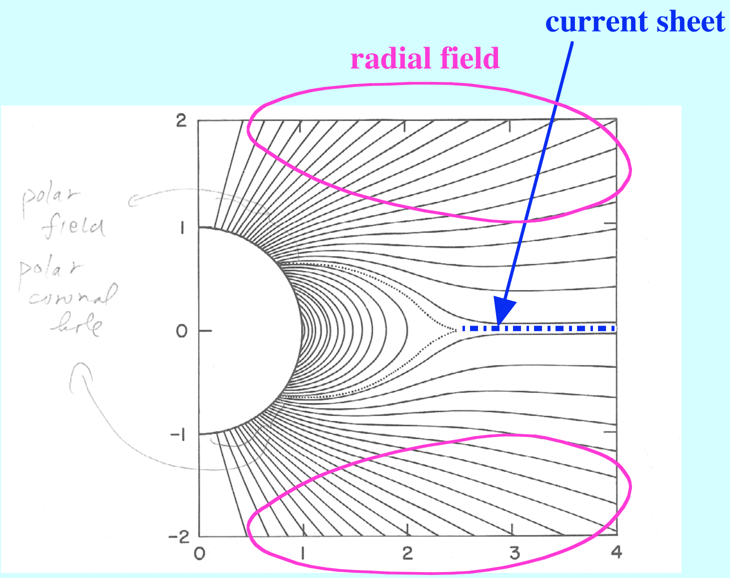
(axis-symmetric, on a meridional plane, isothermal, steady, dipole configuration, no rotation)

r & θ–components of a vector









field lines and **stream lines** (they are parallel because of a steady state)

Basic equations (steady)

$$\nabla \bullet (\rho \boldsymbol{v}) = 0$$

$$\rho (\boldsymbol{v} \bullet \nabla \boldsymbol{v}) = -\nabla p + \boldsymbol{j} \times \boldsymbol{B} - \frac{G M_{\odot} \rho}{r^2} \hat{\boldsymbol{r}} = 0$$

$$T = const.$$

$$\nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0$$

Boundary condition (at the solar surface)

$$\rho = \rho_0 \qquad B_r = B_0 \cos\theta \qquad T_0 = 1.56 \times 10^6 K$$

$$\left(p_0 = \frac{\rho_0}{\mu} k_B T_0 = \frac{B_0^2}{2\mu}\right)$$

Comparison with a potential field

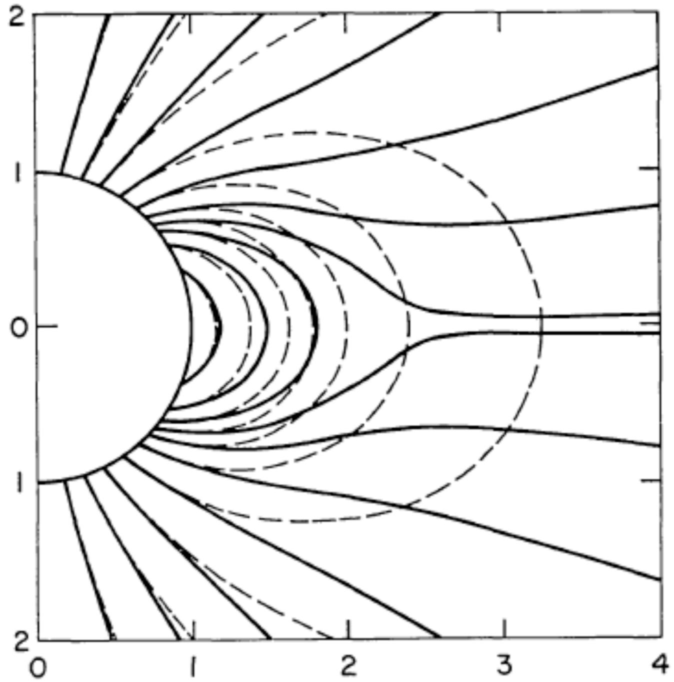


Fig. 8. A comparison of the magnetic field of Figure 3 (solid curves) with a potential field (dashed curves) having the same normal component at the reference level. The field lines for the two configurations are chosen so as to be coincident at the surface.

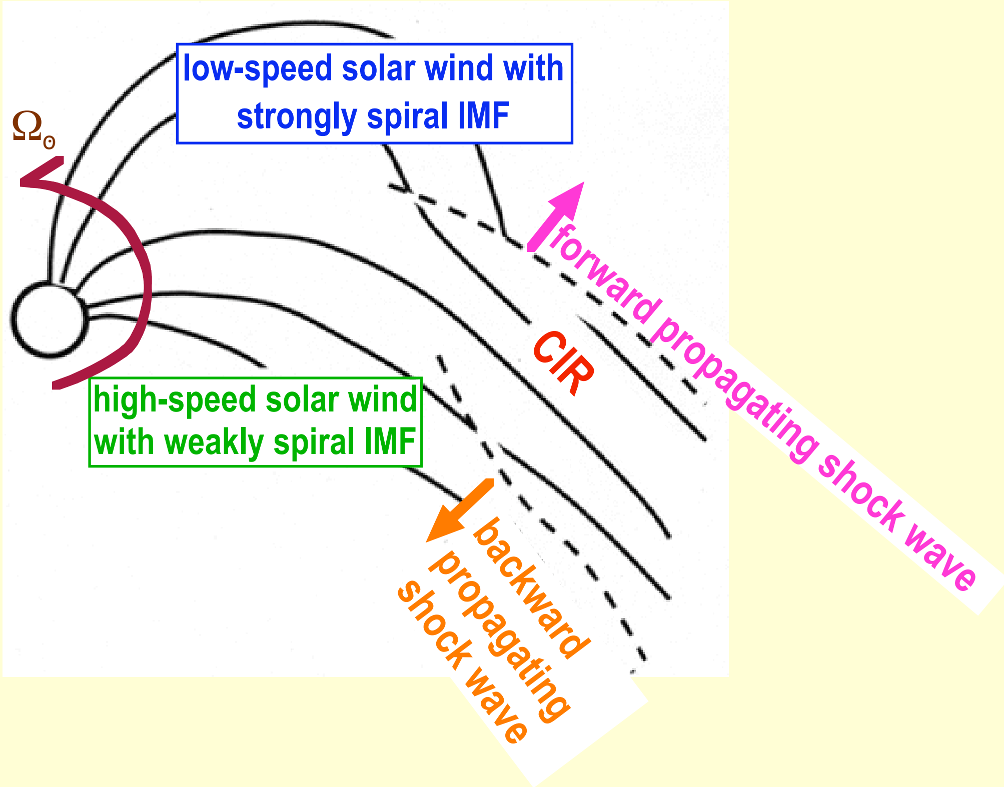
Non-steady phenomena in solar wind

CIR (corotating interaction region)

ICME (interplanetary coronal mass ejection)

CIR (Corotating Interaction Region)

CIR… A region where a high-speed solar wind interacts with a low-speed solar wind ahead. This is a location where MHD shock waves can be produced.



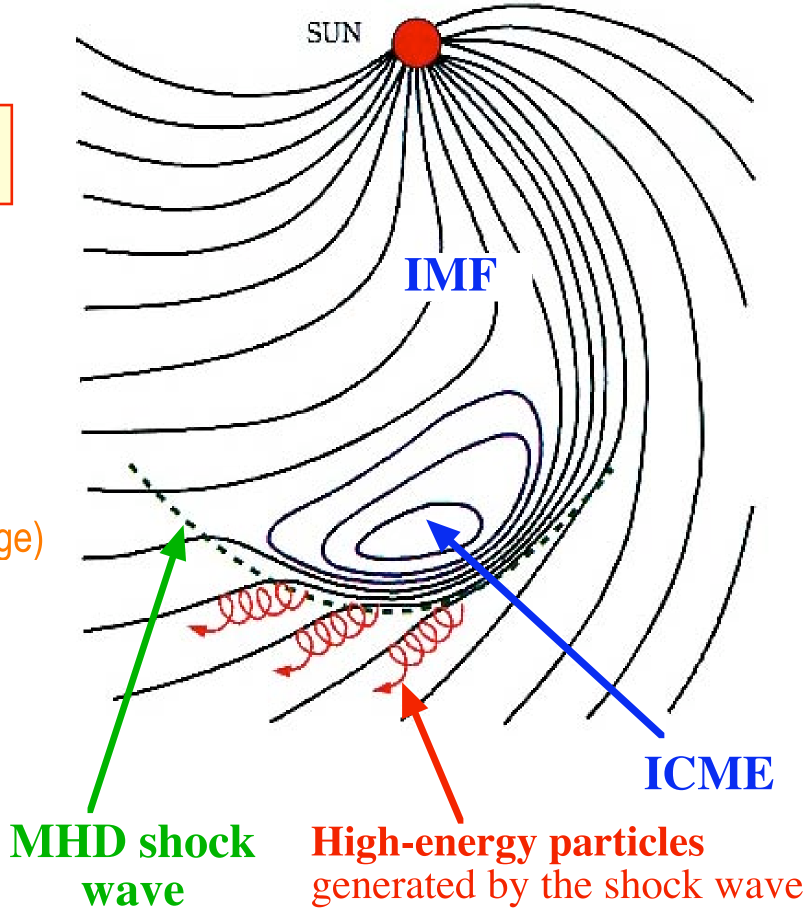
ICME

ICME speed > sound speed, Alfvén speed

↓

MHD shock wave

- **radio emission**
  observed as type II burst (metric range)
  due to plasma oscillation driven by MHD shock wave
- **particle acceleration**
  via scattering process



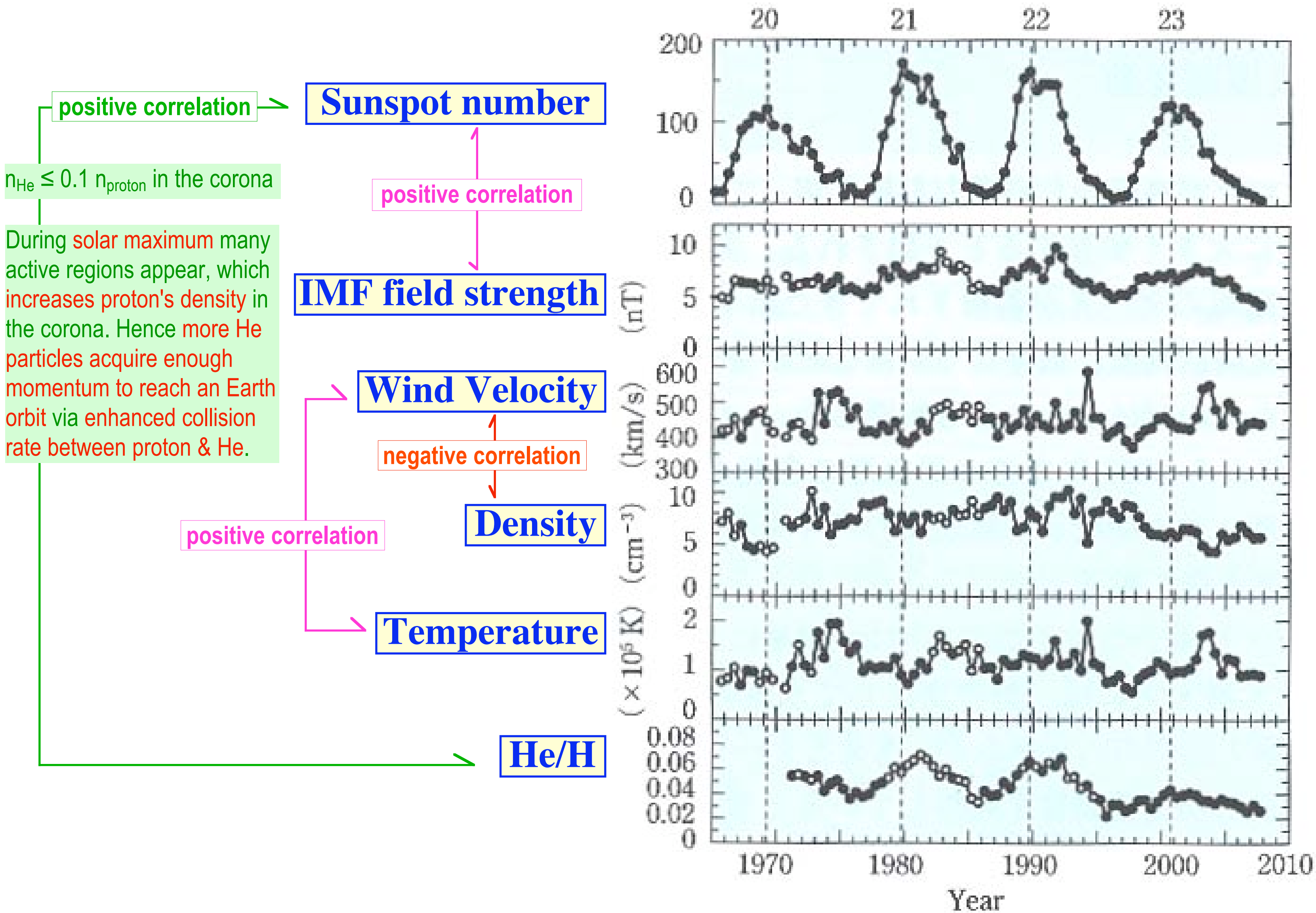
Energy ~ 100 Mev => relativistic proton ($v_p \geq 0.3\ c$)

=> It takes about 20 min. to travel from the corona to the Earth.

=> The high-energy proton can penetrate the terrestrial magnetic field's barrier (**proton event**).

Long-term variation of solar wind

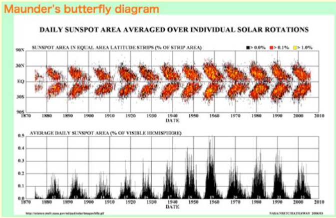
Solar wind variations over multiple solar cycles



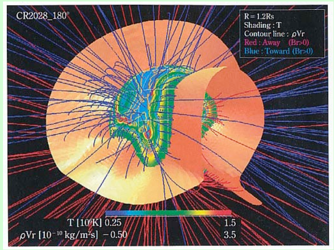
Three key factors determining physical properties of solar wind...

Solar activity

related to **magnetic field strength**



Global magnetic field configuration



Generation mechanism of SW plasma

related to **solar atmospheric heating** & **mass supply from the photosphere to the corona**