Questions

Which one of the following is higher:

Mass loss of sun due to nuclear fusion?

Mass loss of sun due to ejected particles (in context of Solar Wind)?

What is the mass loss of the sun due to the Solar Wind?

$4 \cdot 10^4$ tons per second

$1.5 \cdot 10^6$ tons per second

$4 \cdot 10^6$ tons per second

$4 \cdot 10^8$ tons per second

The Solar Wind (SW)

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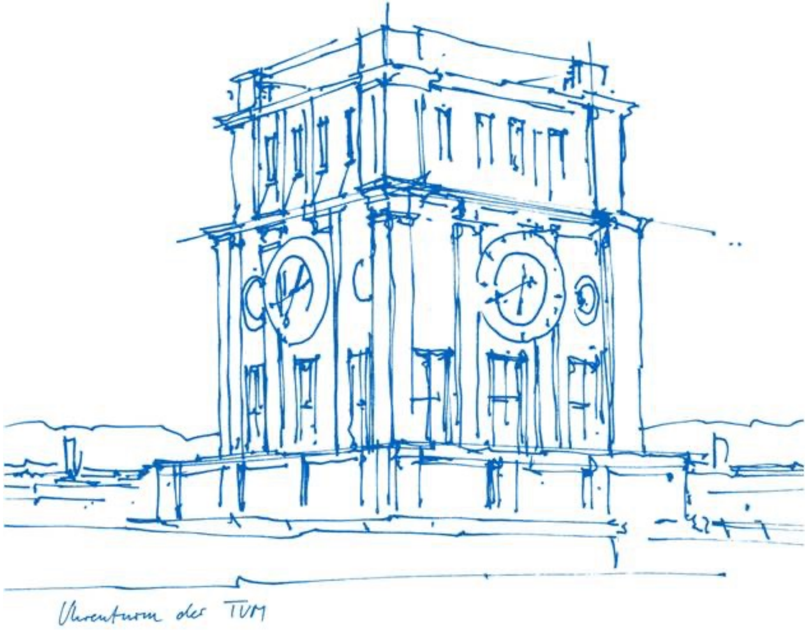
Garching, 09/01/2024

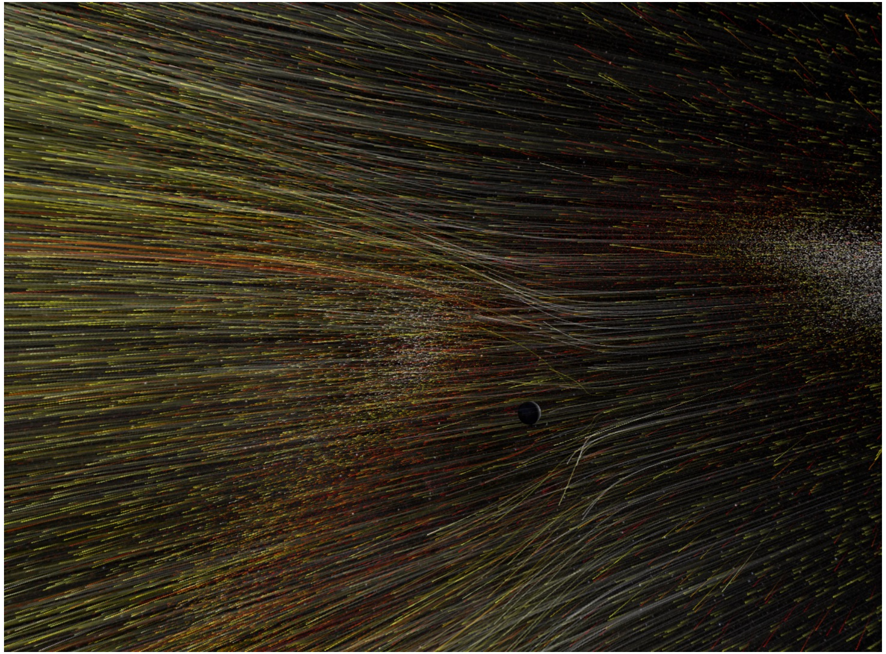


Motivation: Aurora in Bavaria (05.11.2023)

C.Fischer in: BR24

Structure

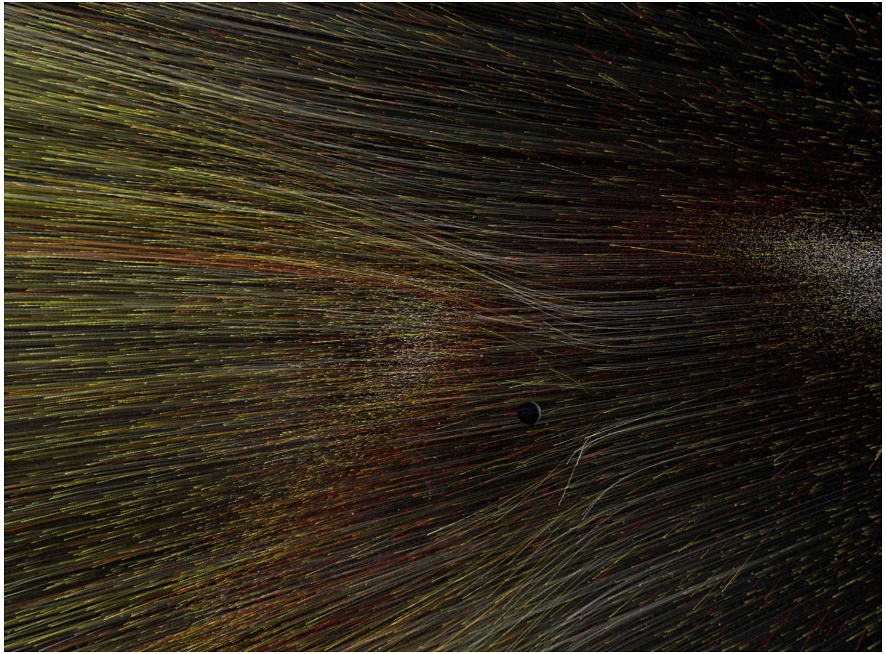
- General information
- History
- Origin
- Heliospheric current sheet
- Models
  - Static model
  - Parker´s solar wind model
- Interaction with earth magnetic field



NASA/Goddard Space Flight Center Scientific Visualization Studio

General information on Solar Wind (SW)

- SW ≙ Stream of plasma from sun, contains electrons and protons
- In contrast to outbursts: permanent
- Not homogenous density, temperature / velocity
- Not constant in time
- Not constant in orientation
- Despite this: simple hydrodynamic phenomenon



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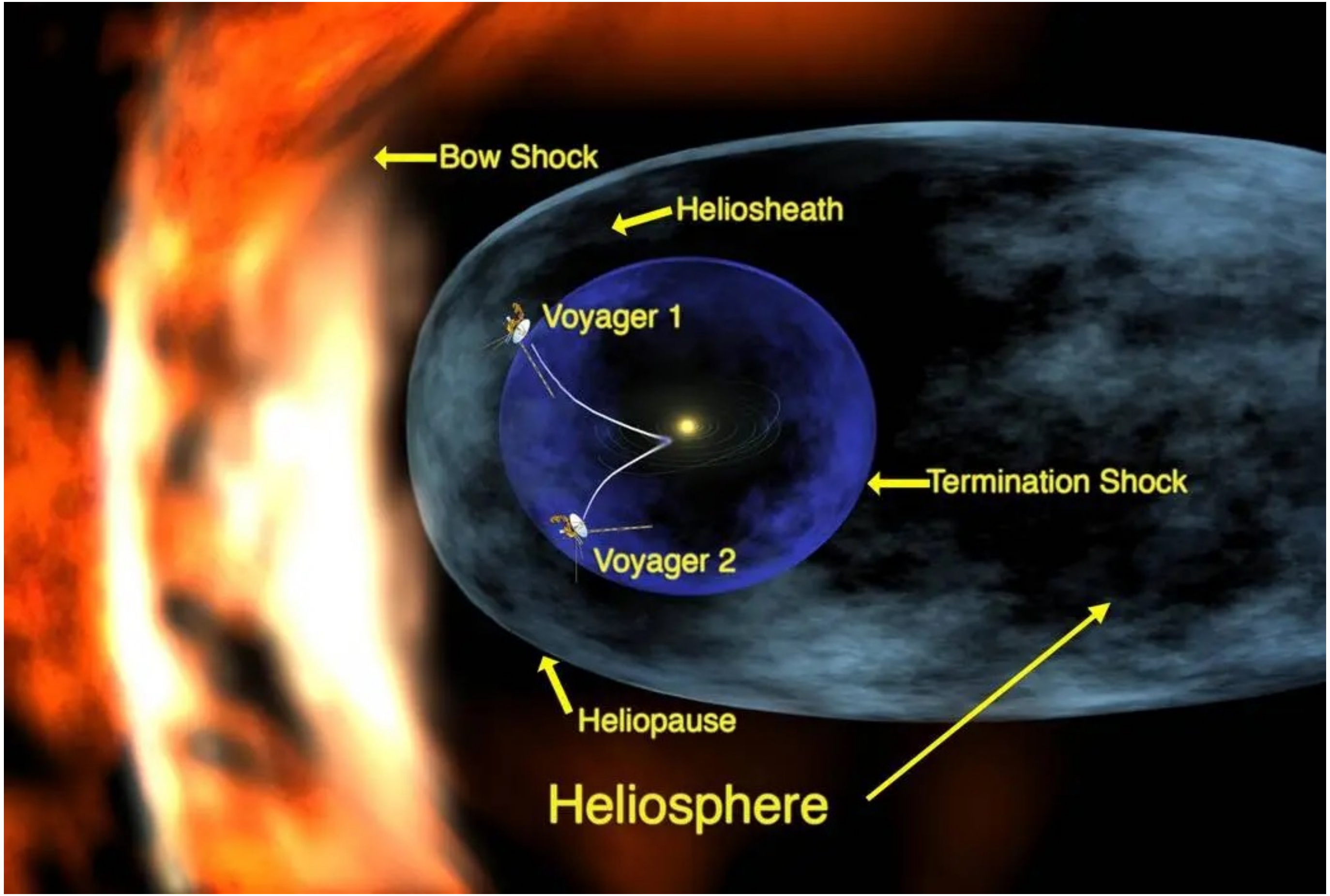


NASA/Goddard/Walt Feimer (2013) | https://www.nasa.gov/image-article/heliosphere-4/

Hydrodynamic observables

- **Velocity**: slow and fast SW
  - At 1 AU (1 AU = $1.5 \cdot 10^{11}$m): 300 to 1400 km/s, average: 500 km/s

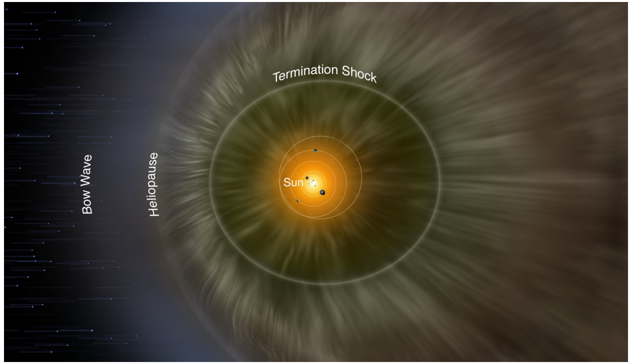
- **Density**: decreases with r^2:
  - At 1 AU: ≈ 7 particle per cm^3
  - At 80 AU: $\approx$ 0.001 particles per cm^3
  - At Heliopause: more particles

- **Pressure** $\approx$ nPa at 1 AU

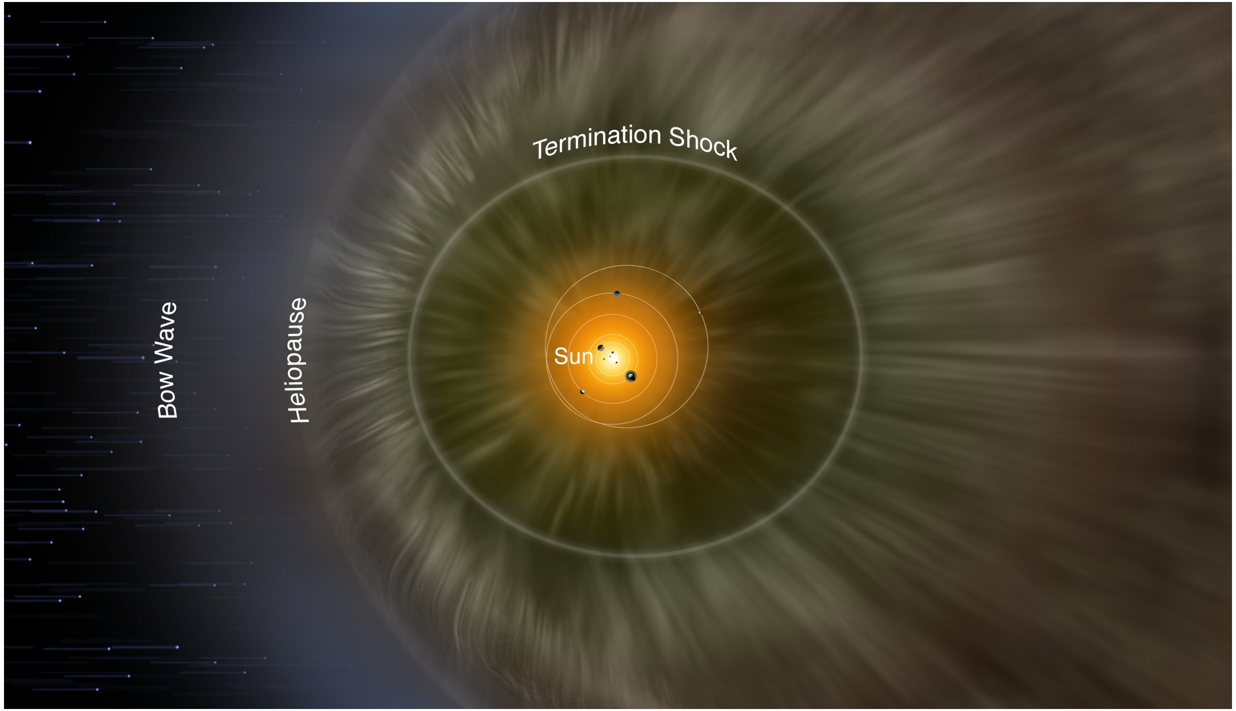
- **Temperature**:
  - At 1 AU $\approx 10^5$ K
  - Compare to:
    - Corona $\approx 10^6$K
    - Surface of sun $\approx 6 \cdot 10^3$K
- Thermical energy and magnetic fieldenergy at 1 AU same $10^{-11}\mathrm{J/m^3}$

General information

- Area of SW (= Heliosphere): Larger than solar system
- Sun is moving fast → stretched out
- Faster than speed of magnetoacoustic waves = supersonic
- At Termination Shock (100 AU): supersonic becomes subsonic
  - SW ‚dodges‘ and moves away to side



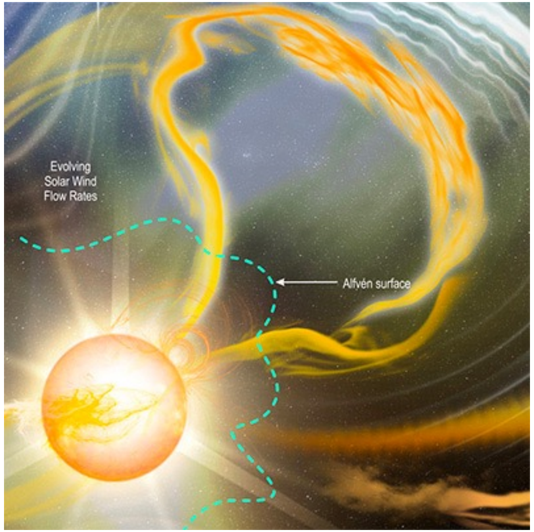
Shape and structure of solar wind



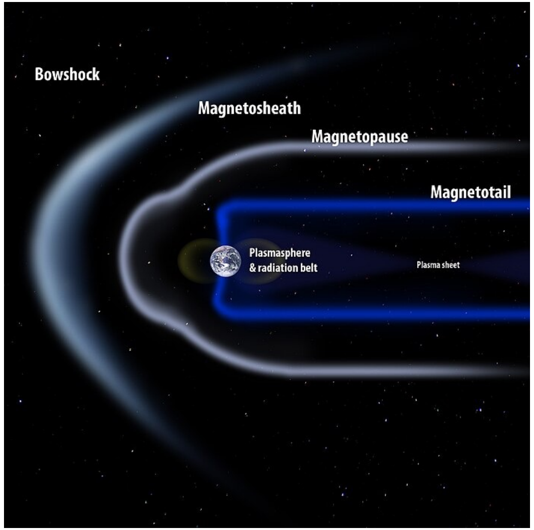
NASA/IBEX/Adler Planetarium

Shape and structure of solar wind

- SW starts ca. in distance $3 \cdot R_s$
- SW ends in approx. 150 AU
- Alfvén waves: borders between corona plasma and SW
- Heliopause: highly turbolent (blocks cosmic rays)



punch/https://punch.space.swri.edu/punch_science_overview.php



Wikipedia Magnetopause

History

- First suggestions: 1850s

- 1930s: discovery of high temperature of corona
  - Temperature of outer parts of sun (Corona): T > 10^6K
- 1951: L. Biermann (Max Planck Institute for Physics) postulated SW based on observations of comets

- 1957: E. Parker mathematical description of SW based on previous model

- First measurements of SW:
  - 1959 Luna 1 (Soviets)
  - 1962 Venus Mariner (Americans)

Origin

- Corona: very high conductivity

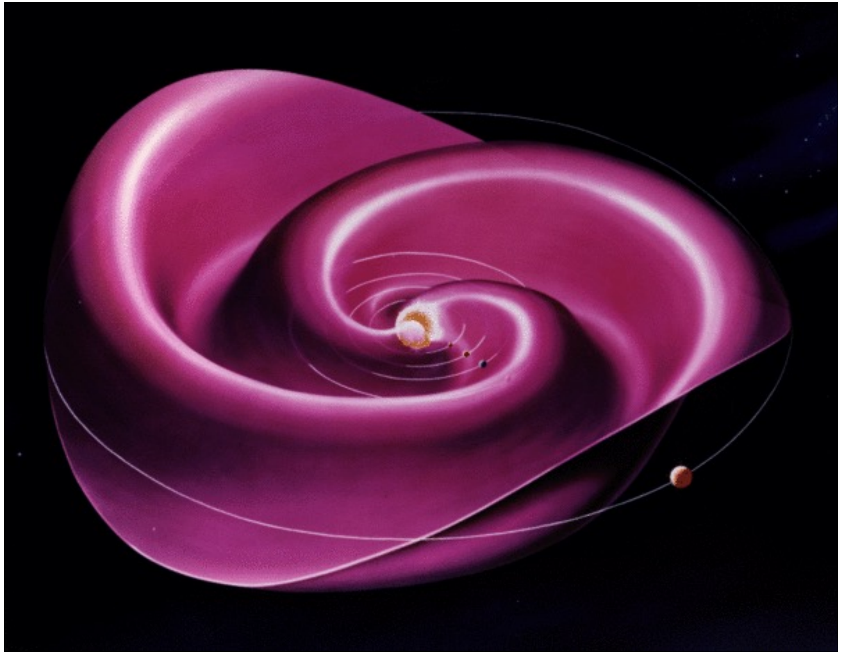
- Thermal-energy-acceleration alone not sufficient for the high speed of SW
- → Various mechanisms for acceleration
- Electrons with velocities higher than escapevelocity build up electic field, leading to further accereration of ions

- Overcoming gravitational binding: temperature of corona decreases less rapidly than 1/r

- Enthalpy converted to kinetic energy, temperature falls → gas expansion velocity increases

- Exact mechanism of heating of corona / SW unknown

Heliospheric current sheet



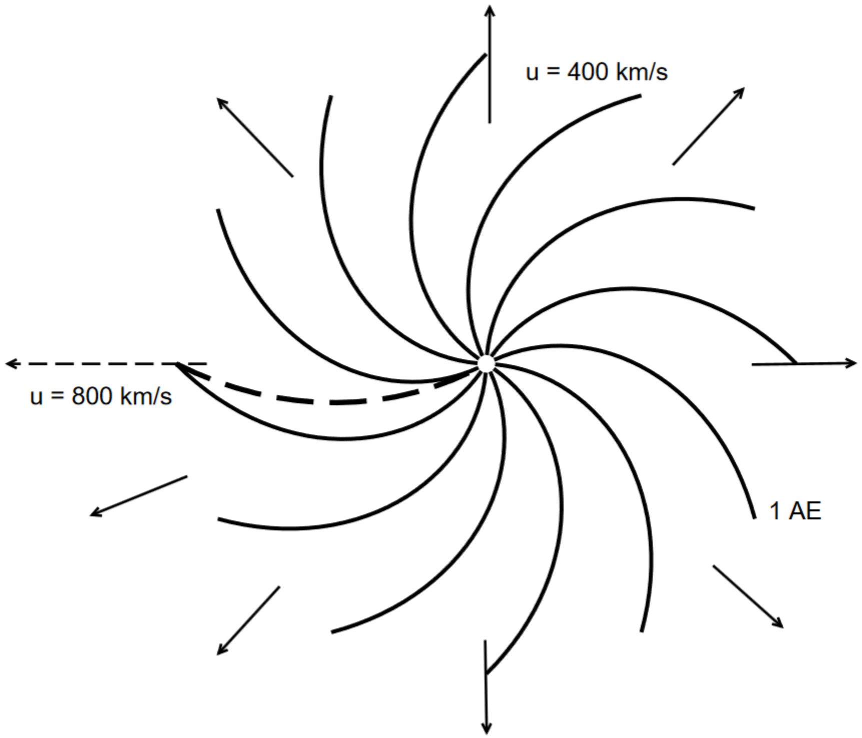
NASA

Heliospheric current sheet

- Parker spiral as a result of differential solar rotation
- → Shape: ‚garden sprinkler effect'

- No Lorentz force on current sheet
- Just forces due to thermical movement effect particles

- Symmetry axis (of B-field) tilted
- Extends beyond Pluto
- Only 10^4 km thick



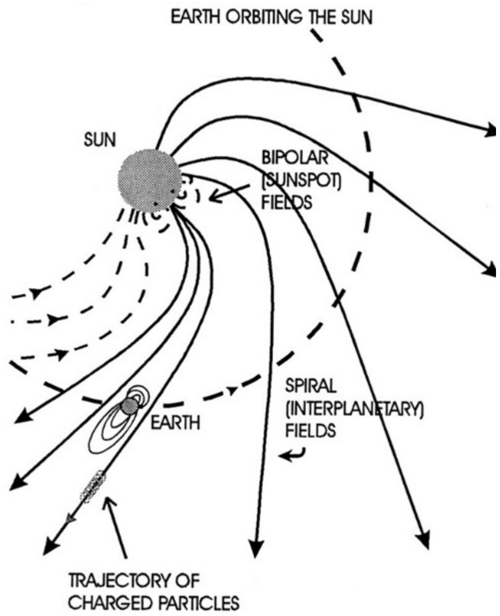
R. Wimmer-Schweingruber: Skriptum zu Plasmaphysik und Extraterrestrische Physik Teil II

Heliospheric current sheet

- Magnetic field (Interplanetary Magnetic Field) spirals wind either inward or outward
- → 2 magnetic domains are seperated by 2 current sheets
- Changes shape during solar cycle

- Along magnetic equatorial plane:
  opposite open field lines parallel
  → Separated by thin current sheet

- Tilted and warped



Stanford/solar wind

Static model of Corona (Chapman model, 1957)

Unpysical !

v is constant

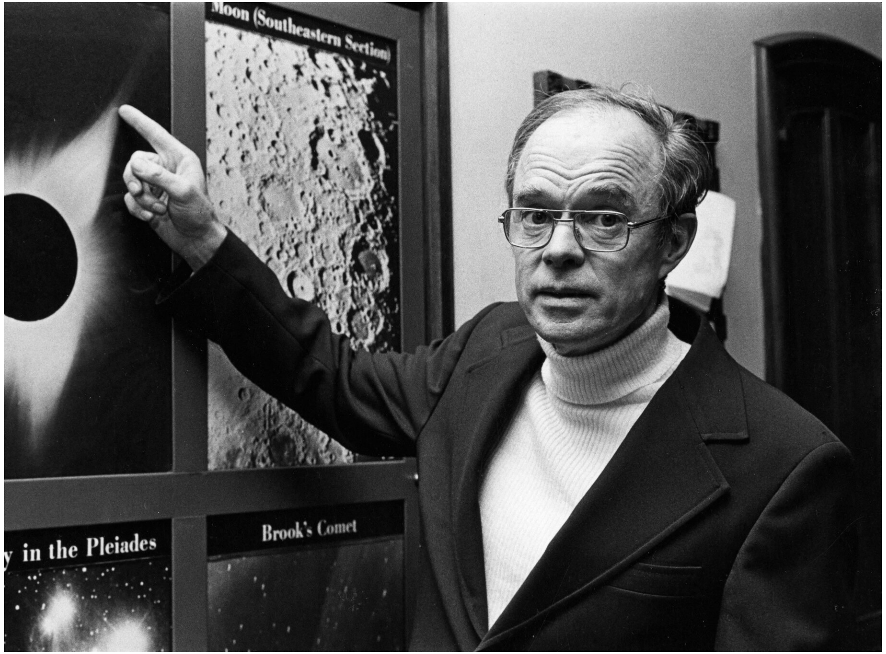
$$\frac{dp}{dr} = -\rho \frac{GM}{r^2}$$

$$T = T_0 \left(\frac{r_{sun}}{r}\right)^{2/7}$$

$$p = p_0 \exp\left(\frac{7GM\rho_0}{5p_0 r_{sun}} \left(\frac{r_{sun}}{r}\right)^{\frac{5}{7}} - 1\right)$$

Parker‘s solar wind model

- Eugene Newman Parker
- 1958: corona could not remain in hydrostatic equilibrium
- Acceleration mechanism lies in magnetic field
- The continual expansion is called SW



University of Chicago / in: NYTimes

Parker‘s solar wind model: derivation

- [Variables used: r distance, v velocity, ρ density, p pressure]
- Assuming radial, steady-state coronal outflow, symmetrical. NO azimuthal velocity !
- Magnetohydrodynamic states that

$$\rho\, v\, \frac{dv}{dr} = -\frac{dp}{dr} - \frac{\rho\, G\, M}{r^2}$$

- Velocity is not constant

Parker‘s solar wind model

With ‚energy equation‘ $p = \frac{2\,\rho\,T}{m}$,

and continuity equation in sph. coord [$r^2 \rho v =$const. → Term $-\frac{2T}{m}\frac{d\rho}{dr} = -\frac{2T}{m}\rho r^2 v \frac{d}{dr}\left(\frac{1}{r^2 v}\right)$] yields:

$$\frac{1}{v}\frac{dv}{dr} \cdot \left(v^2 - \frac{2T}{m}\right) = \frac{4T}{mr} - \frac{GM}{r^2}$$

With $r_c = \frac{GM}{2v_s^2} = \frac{GMm}{4T}$ and $v_s = \sqrt{\frac{p}{\rho}} = \sqrt{\frac{2T}{m}}$ it follows:

$$\frac{dv}{dr} \cdot \left(v - \frac{v_s^2}{v}\right) = 2\frac{v_s^2}{r^2}(r - r_c)$$

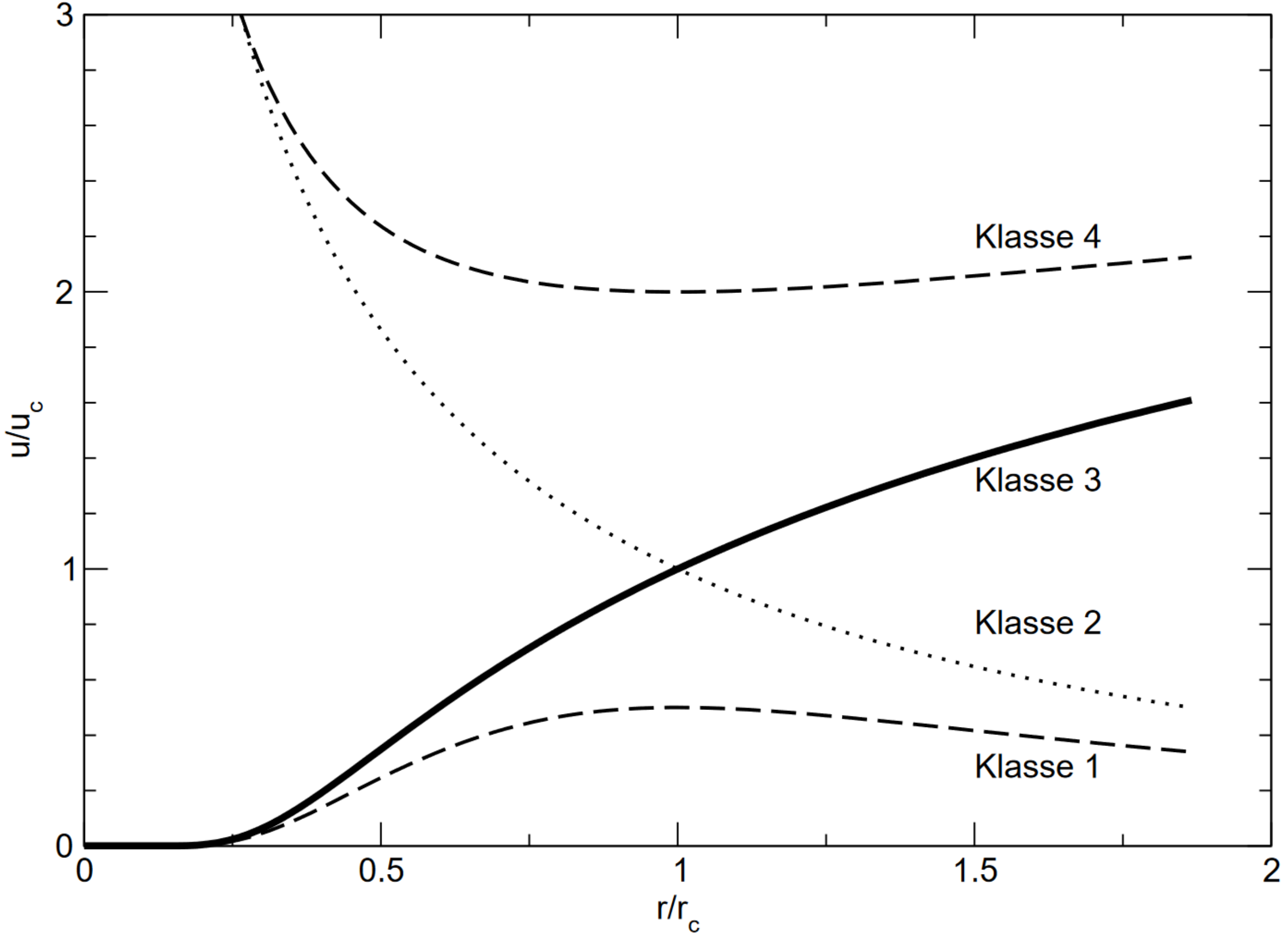
At $r = r_c$ → $v = v_s$

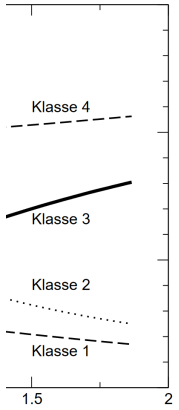
Parke

Reminder:

Solutions v

1. No e
2. Not
3. v in
4. Not





Parker‘s solar wind model

- Reminder: $\left(v - \frac{v_s^2}{v}\right)\frac{dv}{dr} = 2\frac{v_s^2}{r^2}(r - r_c)$
- From integrating (seperation of variables) one obtain:

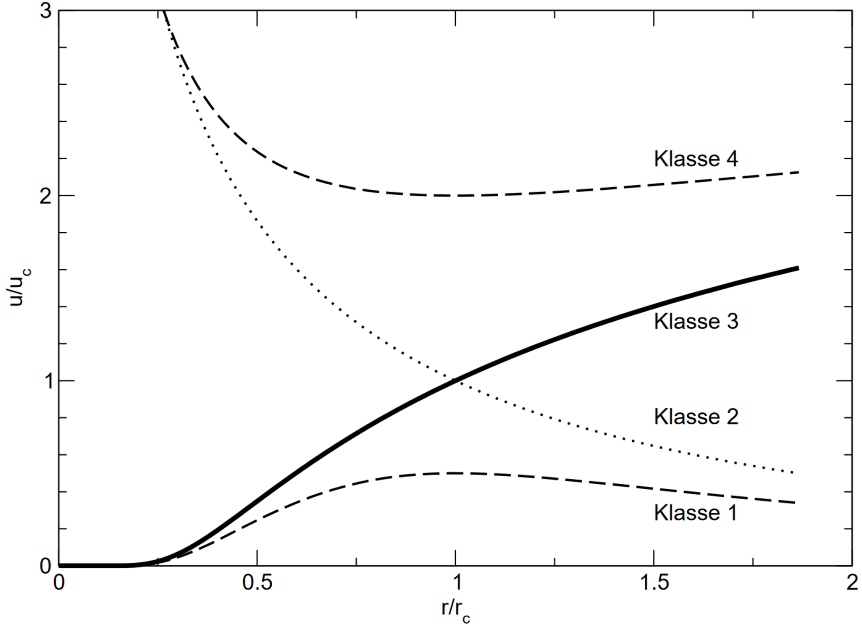
$$\left(\frac{v}{v_s}\right)^2 - 2\log\left(\frac{v}{v_s}\right) = 4\log\left(\frac{r}{r_c}\right) + 4\frac{r_c}{r} + C$$

With $C = -3$ (requested so that $v = v_s$ at $r = r_c$)

- Log is now dimensionless
- Again, sonic (critical) point: $r = r_c \text{ and } v = v_s$

Parker‘s SW model: plots for different C‘s

Plot for v/v_s:



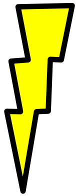
R. Wimmer-Schweingruber: Skriptum zu Plasmaphysik und Extraterrestrische Physik Teil II

to 1.: $\left(\frac{v}{v_s}\right)^2 - 2\log\left(\frac{v}{v_s}\right) = 4\log\left(\frac{r}{r_c}\right) + 4\frac{r_c}{r} + C$

large r → $\log\left(\frac{v}{v_s}\right) \approx -2\log\left(\frac{r}{r_c}\right)$

so $v{\sim}1/r^2$ and $r^2\rho v$ =const.

→ $\rho(r=\infty)$ = finite → p is finite



to 3.: large r → $\left(\frac{v}{v_s}\right)^2 \approx 4\log\left(\frac{r}{r_c}\right)$

→ $\rho(r=\infty) = 0$ → $p = 0$

Parker‘s solar wind model

Concrete values:

$v_s = 10^5 \, \frac{\text{m}}{\text{s}}$ and

$r_c = 7 \cdot 10^9 \text{ m} \approx 10 \, R_{sun}$ << 1 AU

$v_E = 310 \text{ km}/s$ on earth

→ Good approximation: calculated 310 vs 320 $\frac{\text{km}}{\text{s}}$ at earth‘s distance

Parker‘s solar wind model

- Mass loss: $3 \cdot 10^{-14}$ solar masses, or $1.3 \cdot 10^{36}$ particles per second
- $4 \cdot 10^{20}$ W which is about 10^{-6} times total energy output of sun

- Limits / inaccurancies:
  - Desity too high compered to satellite observations
  - Origin of SW not from whole surface
  - Fast SW not covered
  - Same temperature for both protons and electrons
  - In fact: real sun not isothermical

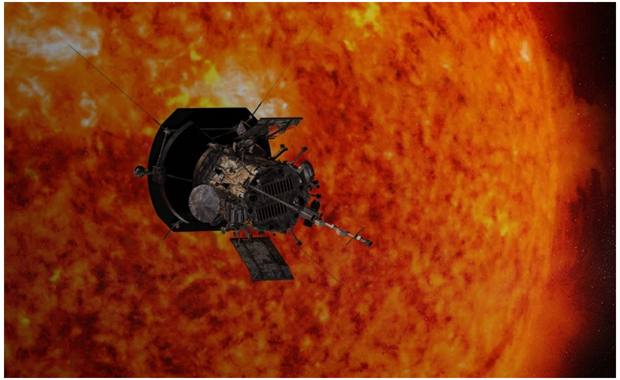
→Only a model (but sufficient)

Parker solar probe

- Named after Parker: 2018 NASA Parker Solar

- Mission:
  - Determine process of acceleration particles
  - Explain enormous difference in Temperature
  - Determine structure and dynamics

- Space weather can
  - Change orbits of satellites
  - Shorten lifetimes
  - Interfere with onboard electronics



NASA/Parker Solar Probe

Solar wind: impact on solar system

- SW can accelerate slower particles from solar flare

- Comet tails
  - Sun emits a steady stream of particles that pushes the comet's tail away

- Interactions with earth magnetic field:
  - Aurora (SW‘s particles deflected by earth‘s magnetic field)

  - Geomagnetic storms (deformation of earth magnetic field)

  - On planets without magn. field: Strip atmosphere away

http://burro.astr.cwru.edu/Academics/Astr221/SolarSys/Comets/tails.html

K. Elfiqi / EPA in: New York Times

Summary & Outlook

- SW as a permanent phenomen of sun
- Parker model describes behavior quite well

- Very complex topic, not fully understood
- Part of recent research
- Active and important ongoing fields of research

List of references

- https://science.nasa.gov/mission/parker-solar-probe/ (04.01.24)
- http://www.scholarpedia.org/article/Parker_Wind (04.01.24)
- H.-T. Janka, E. Müller: lecture notes to Introduction to Theoretical Astrophysics
- U. Stroth Plasmaphysik
- R. Fitzpatrick: Lecture on Plasma Phyics: https://farside.ph.utexas.edu/teaching/plasma/Plasmahtml/node108.html
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- https://www.br.de/nachrichten/bayern/ungewoehnlich-starkes-polarlicht-ueber-bayern,TulP46x (04.01.24)
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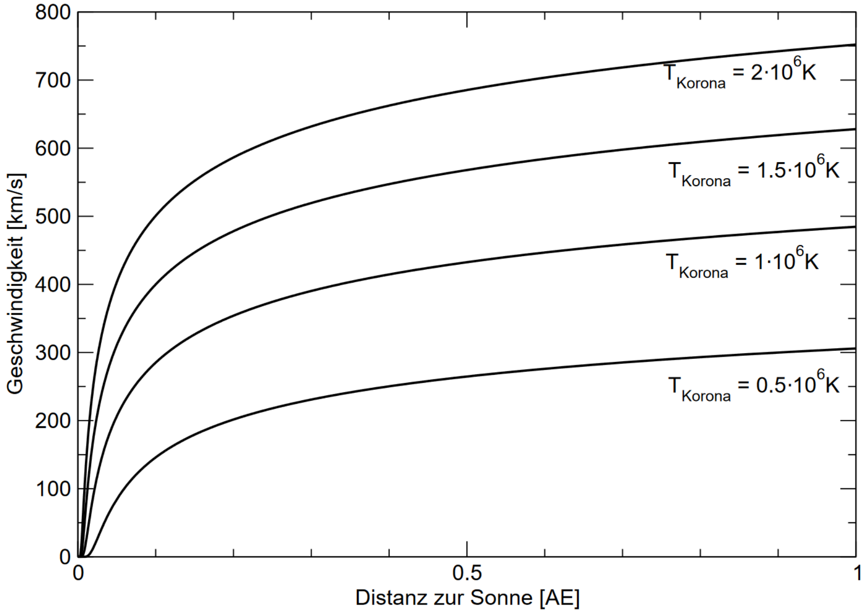
- http://sun.stanford.edu/~sasha/PHYS780/SOLAR_PHYSICS/L22/Lecture_22_PHYS780.pdf (04.01.24)

Joker-Slides

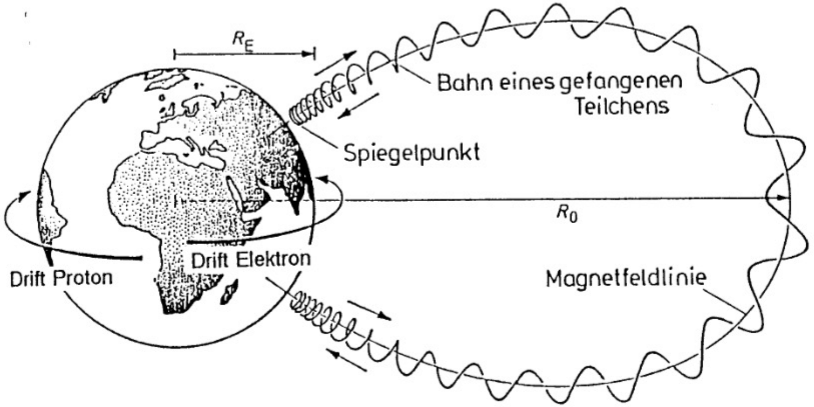


Aurora

NASA/ JSC

Aurora

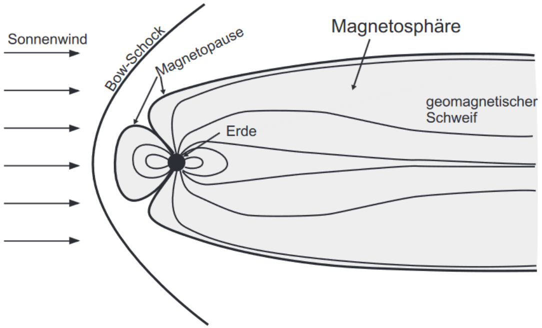
- Solar activity influences earth‘s magnetic field
- Particles escape ‚mirror‘ through collisions
- During entry in atmosphere: aurora



Günter Einführung in Plasmaphysik

More precise: Aurora

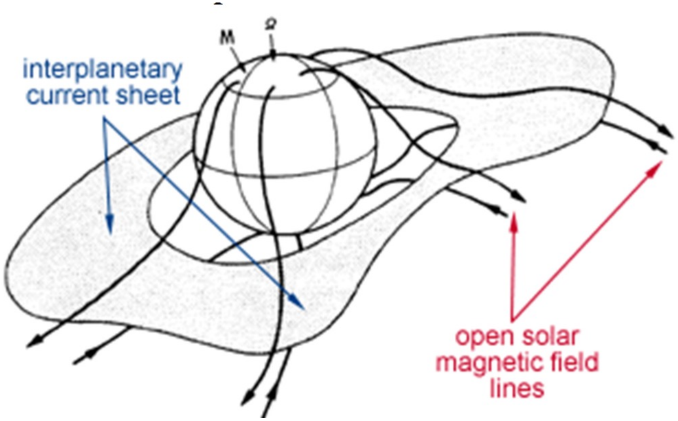
- Also known as northern lights
  - Results of captured particles in Van-Allen-Radiation-Belt
  - Gyrate around magnetic lines, slowly moving towards magn. poles
  - Ionize and excite particles from atmosphere
  - Further information: cf. eg. Stroth Plasmaphysik p. 46ff.



Stroth Plasmaphysik

Heliospheric current sheet

→ Shape: ‚garden sprinkler effect‘ or ‚ballerina effect‘



Stanford/solar wind

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

$$B_\phi = -\frac{B_0 \omega r_0^2 \sin\theta}{vr}$$

$$B_\theta = 0$$

- 1/r term of absolute value of B-field is a consequence of winding up of B-field (not entirely magn. dipole!)

→ Higher magnetic field than dipole

→ Sonic velocity and Alfvén velocity do not have same radial dependence

- Beyond 15 AU: almost toroidal magn. field
- If sun not rotating: radial field

Static model of Corona (Chapman model, 1957)

- No SW because Corona extends to infinity
- Pressure is not approaching 0 for large values of r → unphysical
- Density tends to infinity for large values of r → unphysical
- Hydrostatic equilibrium: $\frac{dp}{dr} = -\rho \frac{GM}{r^2}$
- Thermal conductivity: $\kappa = \kappa_0 T^{5/2}$
- Coronal heat flux density: $q = -\kappa\, \nabla T$, required: $\nabla \cdot q = 0$

Or in spherical coordinates: $-\frac{1}{r^2}\frac{d}{dr}\left(r^2 \kappa \frac{dT}{dr}\right) = 0$

→ $r^2 \kappa_0 T^{5/2} \frac{dT}{dr}$ =const. (seperation of variables)

→ $T^{7/2} = -\frac{C_1}{\kappa_0 r} + C_2$

boundary conditions: large r: T=0 → $C_2 = 0$

$T(r = r_{sun}) = T_0$ → $C_1 = -T_0^{7/2} \kappa_0 r_{sun}$

Parker‘s solar wind model: derivation

- [Variables used: r distance, v velocity, ρ density, p pressure]
- Assuming radial, steady-state coronal outflow, symmetrical. NO azimuthal velocity !
- Magnetohydrodynamic states that

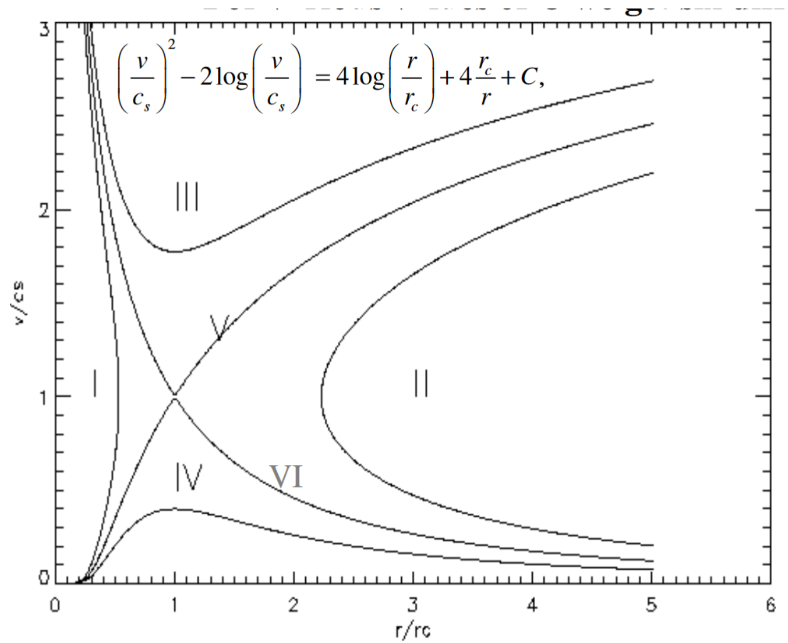
$$\rho\, v\, \frac{dv}{dr} = -\frac{dp}{dr} - \frac{\rho\, G\, M}{r^2}$$

- From hydrostatic equilibrium: ansatz: momentum conservation
  - Gravitational force per unit volume: $\rho \cdot g$
  - Force from below is greater than the force from above by just the amount needed to balance gravity: force per unit volume: ∇p

→ $-\nabla p + \rho g = 0$, standard force per unit volume (Newton) $\rho \frac{d^2 r}{dt^2} = \rho \frac{dv}{dr}\frac{dr}{dt} = \rho\, v \frac{dv}{dr}$

- Alternative access: $dm \frac{d^2 r}{dt^2} = -A dp - \frac{GM}{r^2} dm$ with $dm = \rho\, A\, dr$

More Precise Plot

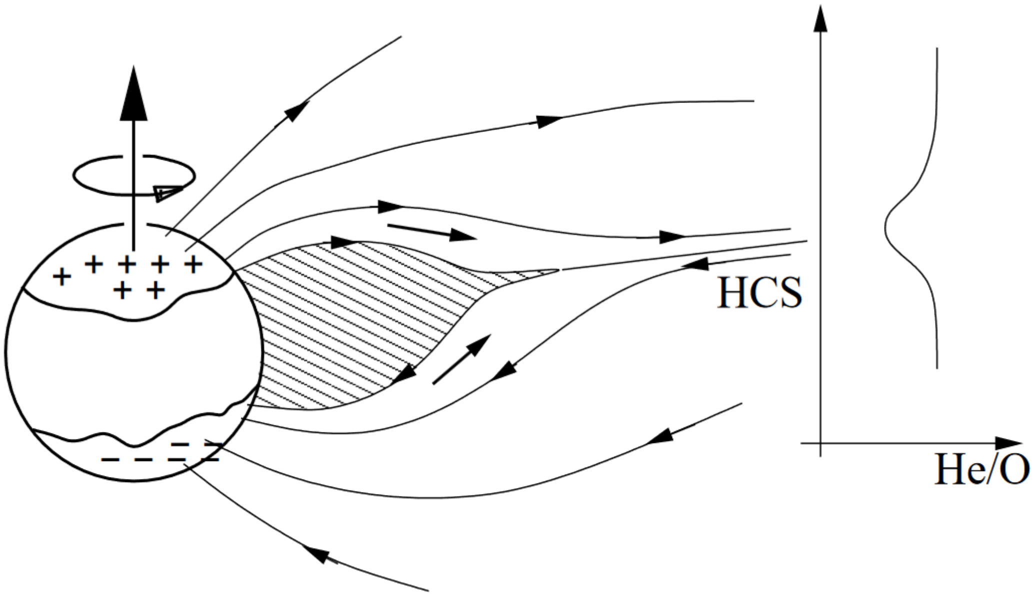


Solution I is doubled valued and so is unphysical. It is not possible for the plasma to leave the solar surface with a velocity below the sound speed, reach a maximum radius below r_c and then turn round and return to the Sun with a super-sonic speed.

Solution II is also double valued but it never even starts from the solar surface and it is also unphysical.

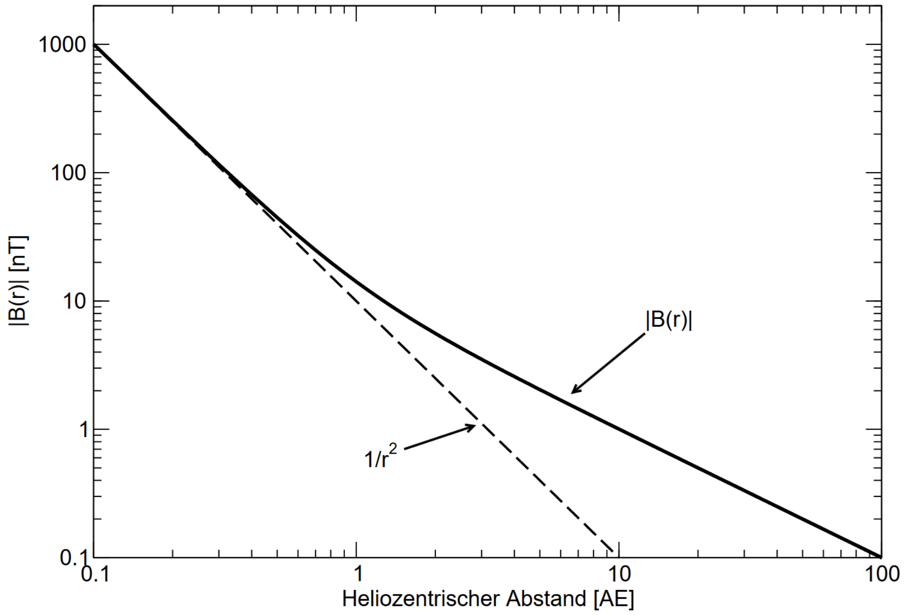
Solution III starts with a velocity greater than the sound speed but such a fast steady outflow is not observed. Hence, this solution must also be neglected.

‚Streamer'



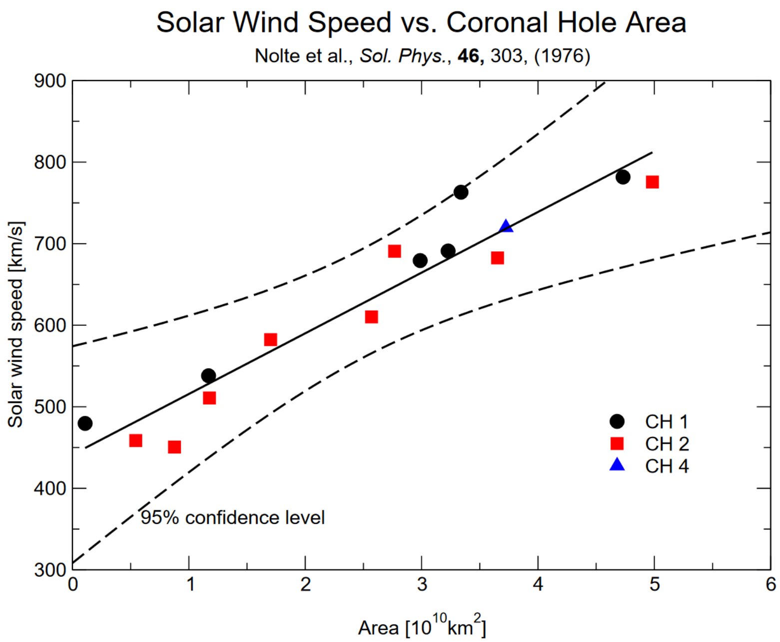
high electron density

Joker-Slides



- At Termination Shock (100 AU, or 1 year of average time for particles): supersonic becomes subsonic
  - Super-Alfvénic becomes sub-Alfvénic $v_A = \frac{|B|}{\sqrt{\mu_0 \rho}}$ Alfvén group velocity (more in other presentation)

Joker-Slides



Joker-Slides

r/R >> 1

$$V^2 \approx 4 \ln\left(\frac{r}{R}\right) - 3 + O(\ln V^2)$$

r/R << 1

$$V(r) \simeq \frac{R^2}{r^2} \exp\left(\frac{3}{2} - \frac{2R}{r}\right)$$

this is hydrostatic barometric law

Joker - slides

$\rho \simeq n\, m_p,$

$\rightarrow \rho = \frac{2\rho T}{m_p}$

~~protons and electrons~~

$$T = T_0 \left(\frac{r_{sun}}{r}\right)^{2/7}$$

$p = 2\, n\, T.$

$$\frac{dp}{dr} = - \frac{p\, m}{2T} \frac{GM}{r^2}$$

$$\int \frac{1}{p}\, dp = \int - r^{-2+\frac{2}{7}} \frac{GMm}{2 T_0 r_{sun}^{2/7}}\, dr \rightarrow \ln \frac{p}{p_0} = C + \frac{7}{5} r^{-\frac{5}{7}} \frac{GMm}{2 T_0 r_s^{2/7}}$$

$$\rightarrow p = p_0 \cdot \exp\left(\frac{7}{5} \frac{GMm}{2 T_0 r_{sun}} \frac{r_s^{5/7}}{r^{5/7}} - 1 \right)$$