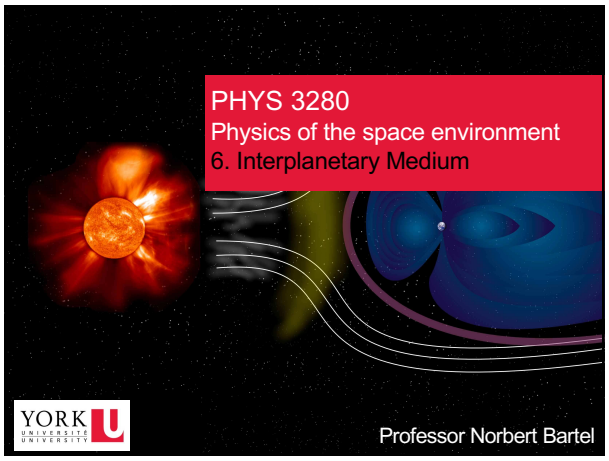

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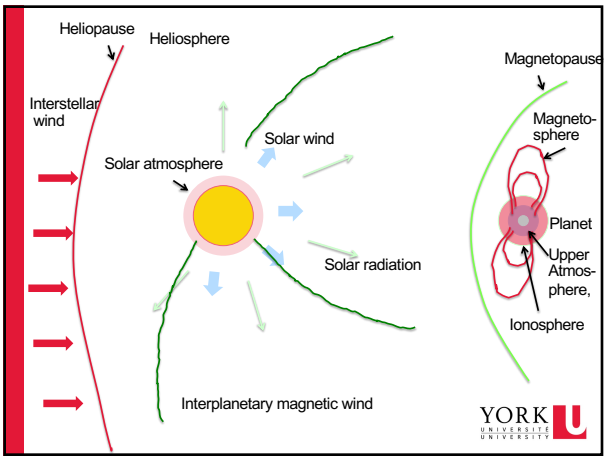


2

Recall: History

Groundbased observations of the interplanetary medium

1942 Alfvén – extremely hot, ionized outer atmosphere
1951 Biermann – plasma flow from Sun on basis of comet tail observations
1958 Parker – Model of solar wind and interplanetary magnetic field

3

Recall: History

- 1970 Nobel Prize for work on magnetohydrodynamics

Hannes Alfven
1908-1995

4

Recall: History

- Showed that the tail of ions of a comet flows away from the Sun with a speed of > 400 km/s.

Ludwig Biermann
1907-1986

5

Recall: History

- Developed the theory of supersonic wind in the interplanetary space
- Developed the model of the "Parker Spiral of the magnetic field in the outer regions of the interplanetry space

Eugene Parker
1927 -

6

Recall History:

Groundbased observations related to the aurora

1733 de Mairan –description of auroras and speculation about the cause: solar particles penetrate Earth's atmosphere and generate polar lights.

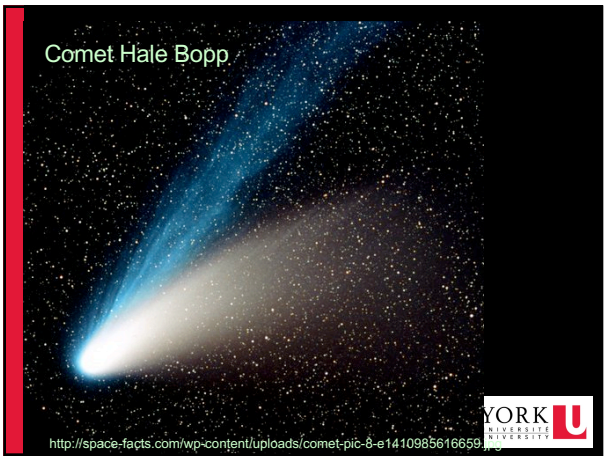
1741 Hjorter & Celsius – Intense magnetic field perturbations occurred during enhanced auroral activity

1866 Ångström– Recording of prominent greenish yellow auroral line at 557.7 nm

~1895 Birkeland – First experimental simulation of an aurora

~1895 Størmer – Calculation of trajectories of electrical particles in Earth magnetic field

7



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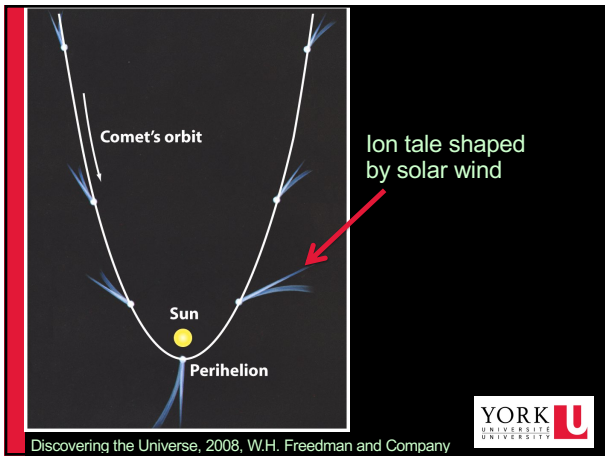

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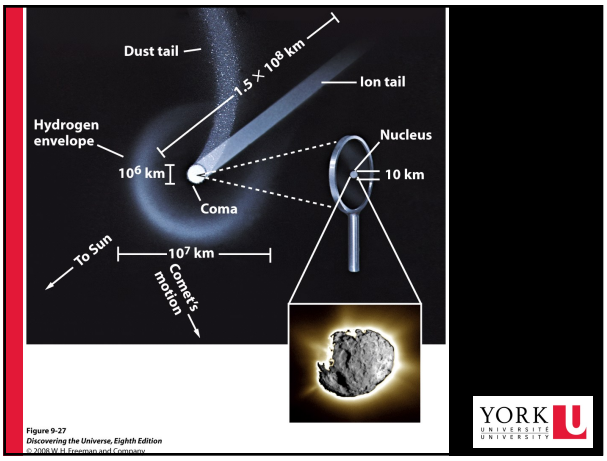

10

Components of the interplanetary medium

- Solar wind :
  - p, e, He^{++} at 1AU nsw~5 x10^6 m^{-3} (5 cm^{-3})
  - Originates in the corona
  - carries out the magnetic field from the Sun
  - deflects magnetosphere and tail of comets away from Sun
- cosmic rays
  - High-energy atomic nuclei , 90% p, 9% He^{++} (α particles), even Fe
  - Only 2% e
  - Minority from Sun
  - Most from Galaxy (supernovae) and extragalactic space (perhaps from black hole environment in the centers of galaxies
- dust particles
  - Micrometeoroids orbiting Sun in plane of solar system
  - Origin: collision between asteroids and from comets when passing near Sun
  - 3x10^7 kg yr^{-1} into atmosphere of earth
- magnetic field
  - Solar wind carries out magnetic field from surface of Sun. Attached to Sun. Rotation causes spiral pattern
- electric field
  - Induced by magnetic field

11

Components of the interplanetary medium

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  - Originates in
  - carries out t
  - deflects mag
- cosmic rays
  - High-energy
  - Only 2% e
  - Minority from
  - Most from Ga
- dust particles
  - Micrometeor
  - Origin: collisi
  - 3x10^7 kg yr^{-1}
- magnetic field
  - Solar wind
- electric field
  - Induced by magnetic field

12

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13

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14

Properties of solar wind at 1 AU

Composition:	≃ 96% H^+, 4% (0–20%) He^{++}, e^-		
Density:	$n_p \simeq n_e$	≃	6 (0.1–100) cm^{-3}
Velocity:	$u_p \simeq u_e = u$	≃	470 (170–2000) km/s
Proton flux:	$n_p\, u$	≃	$3 \cdot 10^{12}$ $m^{-2}s^{-1}$
Momentum flux:	$n_p\, m_H\, u^2$	≃	$2 \cdot 10^{-9}$ N/m^2
Energy flux:	$n_p\, m_H\, u^3/2$	≃	0.5 mW/m^2
Temperature:	T	≃	10^5 (3500–$5 \cdot 10^6$) K
Plasma sound velocity:	v_{PS}	≃	50 km/s
Random velocity:	$\bar{c}_p$	≃	46 km/s
	$\bar{c}_e$	≃	$2 \cdot 10^3$ km/s
Particle energy:	E_p	≃	1.1 keV (flow energy)
	E_e	≃	13 eV (thermal energy)
Mean free path:	$l_{p,p} \simeq l_{e,e}$	≃	10^8 km
Coulomb collision time:	$\tau_{p,p} \simeq 30\,\tau_{e,p}$	>	20 d

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15

Solar wind characteristics

- Mean velocity of 500 km s^{-1} ➔3-4 d from Sun to Earth
- Mass loss per year

$$\frac{dM_{SW}}{dt} = n_p u m_H 4\pi (1AU)^2$$

  - That is <10^9 kg s^{-1}
  - With M_{sol}=2x10^{30} kg, that is $\frac{dM_{SW}}{dt}$ ~1x10^{-14} M_{sol} yr^{-1}
  - compare to some red supergiants : $\frac{dM}{dt}$ ~1x10^{-4} M_{sol} yr^{-1} the solar wind mass loss is extremely small.

16

Mass Loss by a Supermassive Star

Gemini/Aura

17

Movie of SN1993J

15 mas
50,000 AU

Explosion Center

from t = 50d (r=200 AU) to t = 22 yr (r=40,000 AU)

Free download: www.yorku.ca/bartel

18

Solar wind characteristics

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- Energy flux

$$\phi_{SW}^E(1AU) = n_p u E_{kin} = n_p u\left(\frac{1}{2} m_H u^2\right)$$ = 0.5 mW m^{-2}

  - compare with 15 mW m^{-2} for UV
  - Compare with 1.37 kW m^{-2} for all EM radiation from Sun
- Total energy loss due to solar wind is $\left(\phi_{SW}^E + \phi_{SW,pot}^E\right) 4\pi (1AU)^2$ = 4x10^{20}W with $\phi_{SW,pot}^E = n_p u E_{pot}$

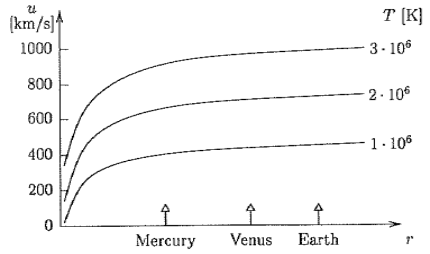
$$E_{pot} = \int_{R_{sol}}^{\infty} m_H g_{sol} dr = \frac{G m_H M_{sol}}{R_{sol}}$$

  --compare with L=4x10^{26} for all EM radiation

Solar wind energy loss only 10^{-6} of EM energy loss!

20

- Solar wind velocity profile (based on theory)



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- Temperature profile
  - Assumption : adiabatic gas expansion into interplanetary medium. ,← no heat exchange takes place between the gas and the environment of the gas. The work for the expansion of the gas is taken 100% from the internal energy of the gas.

$$T = T_0\left(\frac{V}{V_0}\right)^{-\frac{2}{f}}$$

Note: Volume grows with r^2

$$dV = r^2 \sin\vartheta d\vartheta d\varphi dr$$

$$T(r) = T(r_0)\left(\frac{r}{r_0}\right)^{-\frac{4}{f}}$$

$$T(r) = T(r_0)\left(\frac{r}{r_0}\right)^{\frac{4}{3}}$$

➔ For T(r_0)=10^6 K at r_0=3R_{sol} ➔T(1 AU)=3400 K

The lowest T(1AU) measured is indeed so low. So adiabatic expansion plays some role. However, extra heat perhaps from electrons.

22

Recall:Adiabatic changes of state

- Assume change of state of a gas proceeds with no heat exchange with the environment, i. e. ΔQ=0
- Work during expansion done at the expense of own internal energy

$$\Delta Q = \Delta U - \Delta W = 0$$

$$\Delta W = -p\Delta V = \Delta U = Nf\left(\frac{k}{2}\Delta T\right)$$

$$dW = -pdV = dU = Nf\left(\frac{k}{2}dT\right)$$

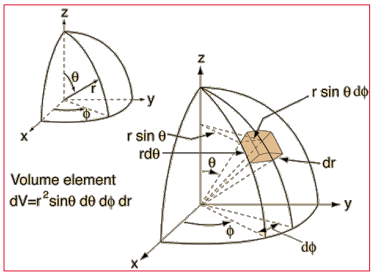
$$\frac{dT}{T} = -\frac{2}{f}\frac{dV}{V}$$ with $N = nV$, $p = nkT$ Integrating➔ $\ln\left(\frac{T}{T_0}\right) = -\frac{2}{f}\ln\left(\frac{V}{V_0}\right)$

$$T = T_0\left(\frac{V}{V_0}\right)^{-\frac{2}{f}} \quad \text{or} \quad TV^{\frac{2}{f}} = const$$ adiabatic law

$$n = const \bullet p^{\frac{1}{\gamma}} \quad \text{or} \quad p\rho^{-\gamma} = const$$ alternative form if N=const.

23

Recall:



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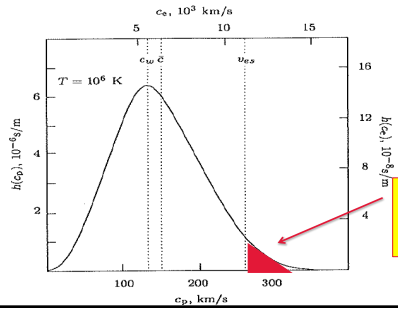
- Escape velocities
  - Can protons and electrons actually leave the corona of the Sun? For a realistic calculation, one has to take into account that electric forces, similar to the scenario in the ionosphere,



ion.

p and e escape from corona

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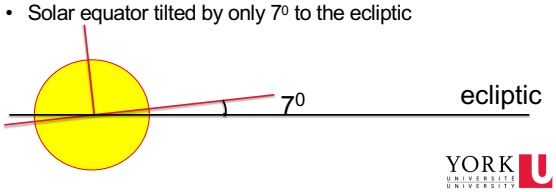
Large-scale solar wind structure

- Solar wind structure is NOT spherically symmetric
- Low solar latitudes are in areas of closed magnetic field lines
- High solar latitudes are in areas of open magnetic field lines
- Solar equator tilted by only 7^0 to the ecliptic



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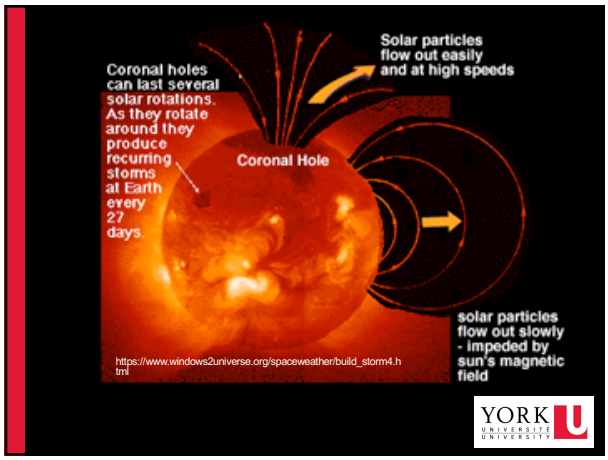

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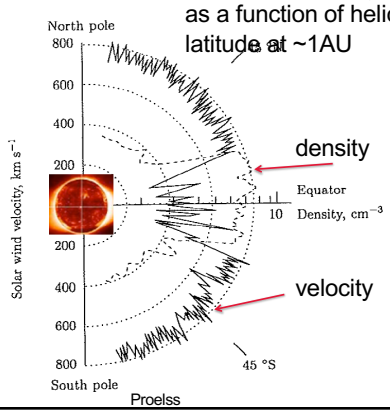
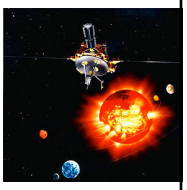
Solar wind velocity and density as a function of heliographic latitude at ~1AU



Ulysses–ESA/NASA mission



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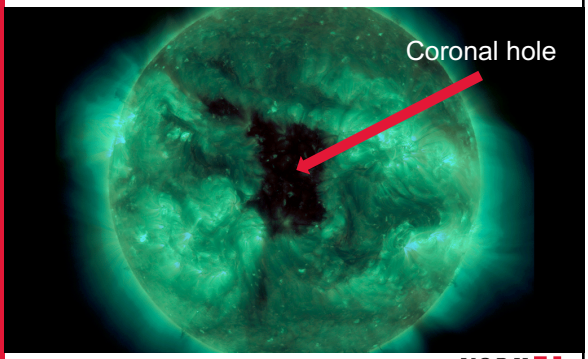
X-ray image of the Sun



https://briankoberlein.com/wp-content/uploads/coronalhole-1030x611.png

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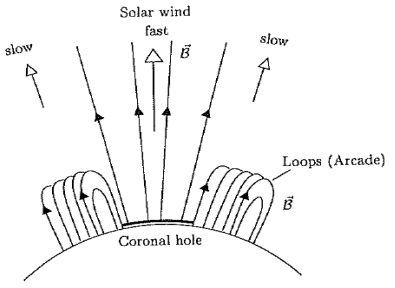

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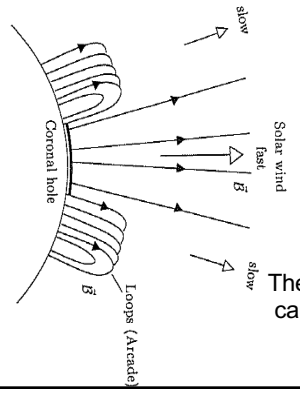
Solar wind in the ecliptic



The rotation of the Sun causes a spiral to form

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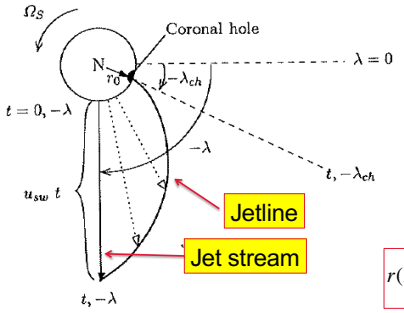
Jetline and jet stream



$$r(t) = r_0 + u_{sw} t$$

$$t = \frac{(-\lambda + \lambda_{ch})}{\Omega_S}$$

and for

$$\lambda < \lambda_{ch}, r >> r_0$$

$$r(\lambda) \cong -\frac{u_{sw}}{\Omega_S}(\lambda - \lambda_{ch})$$

Jetline follows an Archimedean spiral (Parker spiral)

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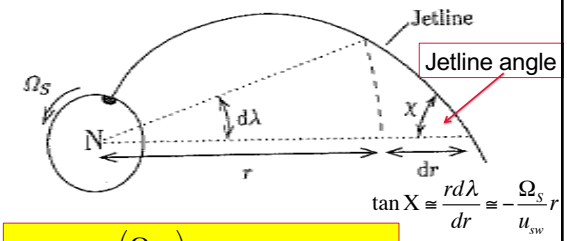
Jetline angle



$$\tan X \cong \frac{r d\lambda}{dr} \cong -\frac{\Omega_S}{u_{sw}} r$$

$$|X| \cong \arctan\left(\frac{\Omega_S}{u_{sw}} r\right) \cong \arctan(0.9 \bullet r[AU])$$

At Earth: X=43^0

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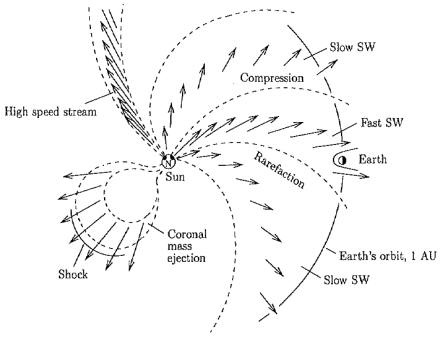
Solar wind structure in the ecliptic



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- The solar wind spiral is structured into different sectors
- Each zone is anchored to a coronal hole
- Slow solar wind produces broad sectors, fast solar wind produces narrow sectors
- That leads to rarefaction and compression at the boundaries

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Interplanetary magnetic field

- Parameters measured with interplanetary spacecraft
- Strength of magnetic field at 1AU, B ~ 3.5 (0.2 – 50) nT

$$B_r[nT] \cong \frac{2.6}{r^2[AU]} \qquad B_\lambda[nT] \cong \frac{2.4}{r[AU]}$$

$$|X| \cong \arctan\left(\frac{B_\lambda}{B_r}\right) \cong \arctan(0.9 \bullet r[AU])$$

- Magnetic field lines are oriented parallel to the solar wind jetlines
- Magnetic field polarity changes typically with a cycle of 2 times per Sun rotation period (27 d).

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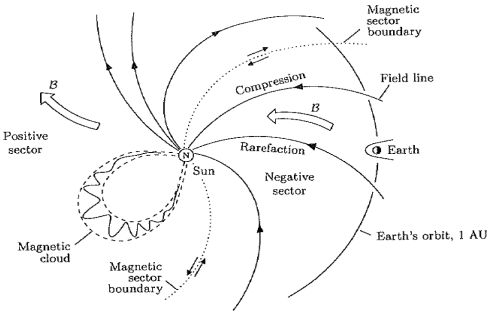
Interplanetary magnetic field in the ecliptic



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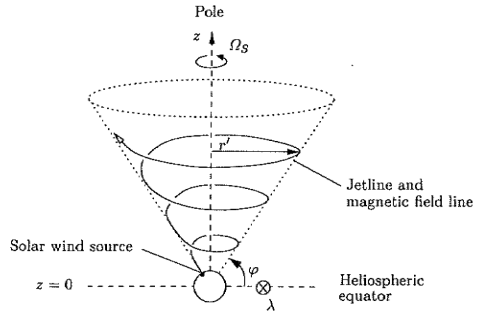
Interplanetary magnetic field outside the ecliptic



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- Similar to the magnetotail neutral current in the terrestrial magnetosphere, there is a heliospheric neutral current
- It is a current flowing in the large circumsolar disc which is basically the ecliptic plane.
- The neutral sheet is between the torn-out magnetic field lines with opposite polarity

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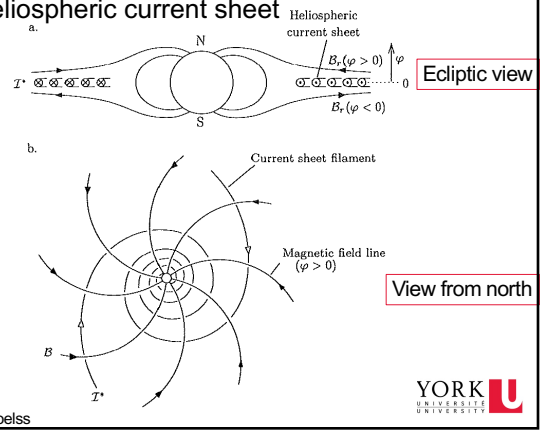
Heliospheric current sheet



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- However a closer look shows that the heliospheric current sheet oscillates around the heliographic equator because of the tilt of the magnetic equator of the Sun wrt. the heliographic equator.
- Earth experiences these oscillations with a period equal to the synodic rotation period of the Sun

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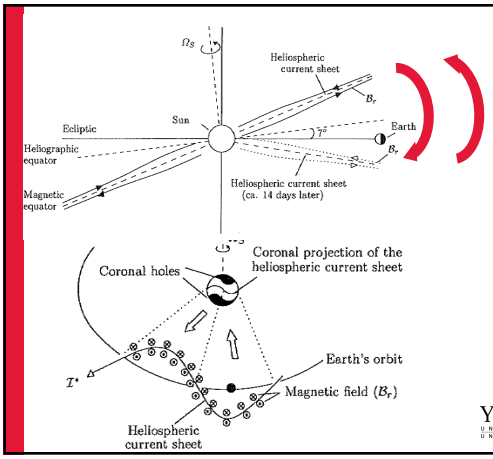

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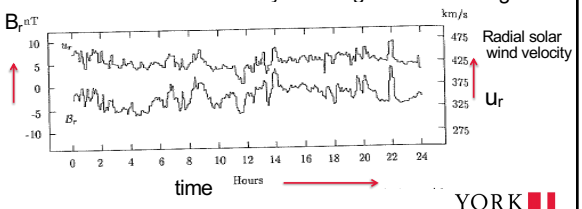
Magnetoplasma waves

- The interplanetary medium is quite variable, temporally and spatially
- Interplanetary spacecraft recordings show a correlation between solar wind velocity and magnetic field strength



Mariner 5 recordings (Proelss adapted from Belcher et al. 1969)

43

- The temporal and spatial fluctuations are largely caused by magnetohydrodynamic waves
- There are three physically different kinds of such waves
  - Plasma acoustic waves
  - Alfvén waves
  - Magnetosonic waves

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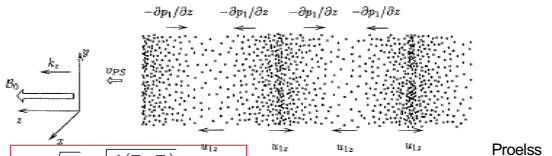
Plasma acoustic waves

- Plasma (p and e) moves along magnetic field
- No magnetic force is experienced, perturbations are described solely by density, pressure and plasma velocity
- Plasma acoustic wave characterized by rhythmic back and forth motion along magnetic field



$$v_{PS} = \sqrt{\frac{\gamma p}{\rho}} \cong \sqrt{\frac{\gamma k (T_i + T_e)}{m_i}} \cong 50 kms^{-1}$$

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For T_i=T_e=10^5K at 1AU

45

Alfvén waves

- No density and pressure variations of the plasma
- Variations in the magnetic and electric field and the current density occur together with the transverse velocity

$$v_A = \sqrt{\frac{B^2}{\mu_0 \rho}} \cong 30 kms^{-1}$$ at 1 AU

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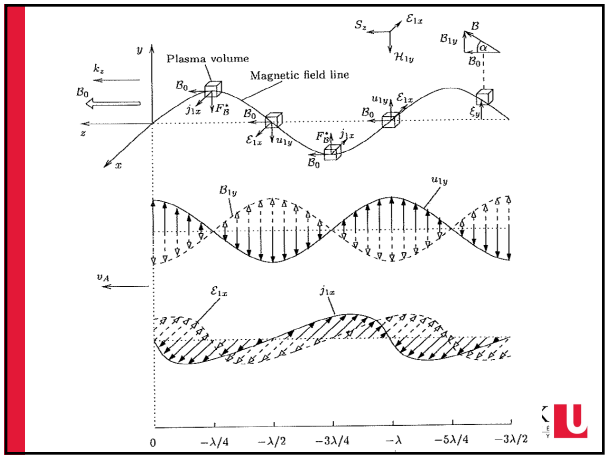

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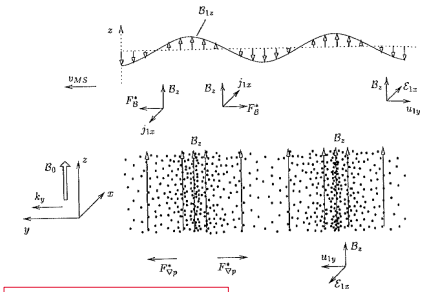
Magnetosonic wave

- Combination of plasma acoustic waves and Alfvén waves



$$v_{MS} = \sqrt{v_{PS}^2 + v_A^2} \cong 60 kms^{-1}$$ at 1 AU

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Interaction of the solar wind with the interstellar medium

- Solar system is moving through the outer edge of an interstellar gas cloud

Parameters of the very local interstellar medium

composition	H: 90%, He: 10%
Density, n_H	0.2 cm^{-3} = 2 x 10^5 m^{-3}
$n_p = n_e$	0.1 cm^{-3}
Velocity, u	25 km s^{-1}
Temperature, T	7000 K
Magnetic field, B	0.15 nT

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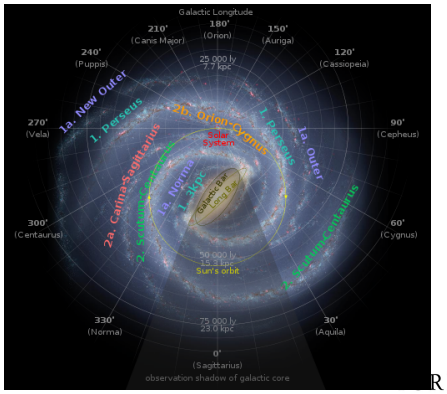

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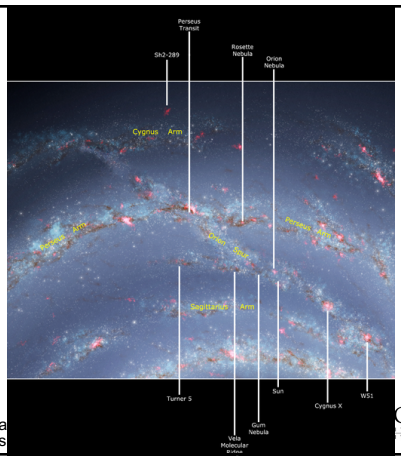

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- Neutral gas particles from the interstellar medium can enter the solar system
- Charged particles from the interstellar medium are reflected by the solar system magnetic field
- Charged particles from the interplanetary medium are reflected by the interstellar magnetic field

- Heliopause is boundary where both velocities are 0.
- Bow shock: where interstellar wind is decelerated to subsonic velocities
- Termination shock: where solar wind is decelerated to subsonic velocities

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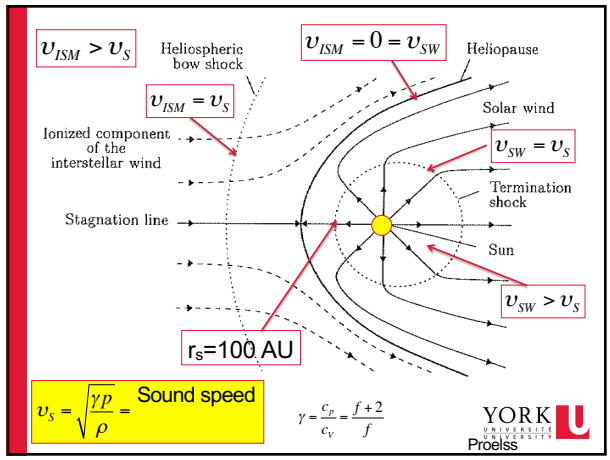

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Proelss

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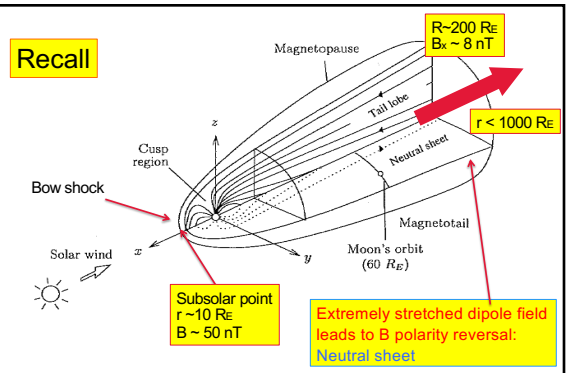

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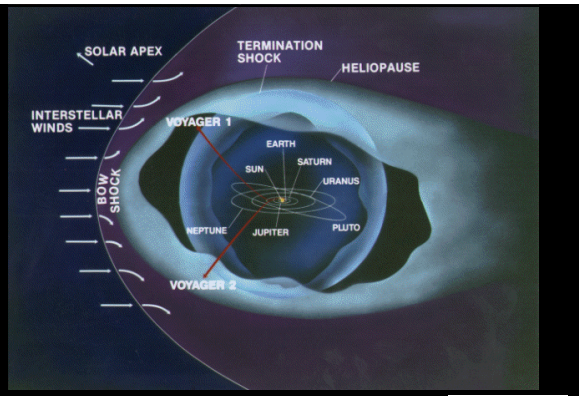

http://voyager.jpl.nasa.gov/mission/images/interstellar_1.gif

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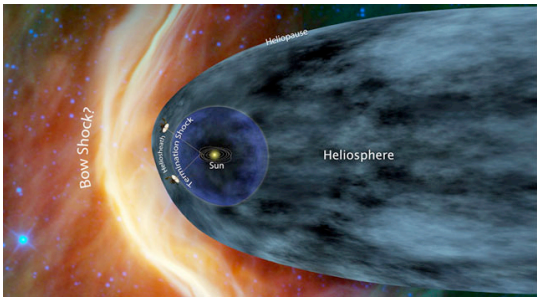
Voyager positions



http://voyager.jpl.nasa.gov/mission/index.html

https://voyager.jpl.nasa.gov/news/details.php?article_id=112

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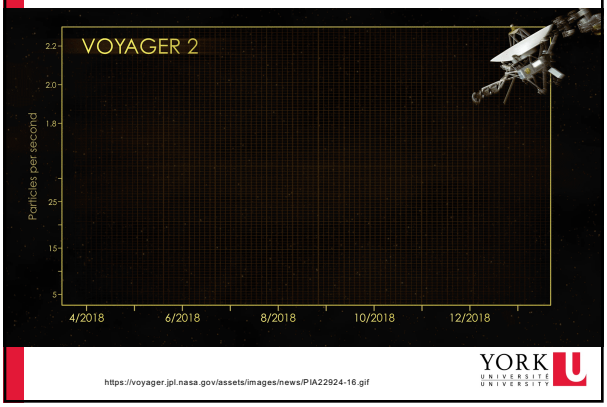

https://voyager.jpl.nasa.gov/assets/images/news/PIA22924-16.gif

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Earth as "Pale Blue Dot"

Distance from Earth: 6 Bill. km

https://solarsystem.nasa.gov/resources/536/voyager-1s-pale-blue-dot/

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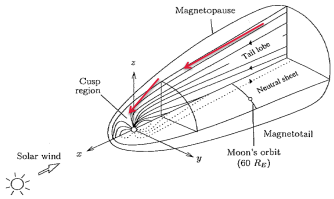
Aurorae

- An aurora is caused by energetic particles impinging on the atmosphere
- Particles are mostly electrons with energies of 100 to 10,000 eV. Some ions are also observed.
- Origin of aurora particles probably from the magnetotail of the magnetosphere



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- The electrons are slowly decelerated in the upper atmosphere in the polar regions
- The energy is absorbed at heights between 100 and 200 km, depending on the energy of the electrons.
- Redistribution of the absorbed energy is complex.
- Ionization and excitation of atoms and molecules in the upper atmosphere lead to emission of light in different colours.
- Violet-blue (N_2^+) , yellow-green (O), red (O, N_2)
- IR and even X-ray auroras can also be measured.

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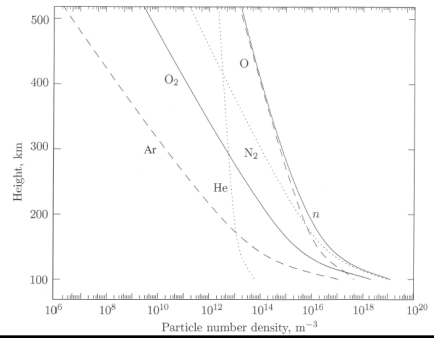
Recall

Particle number density



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Wikipedia

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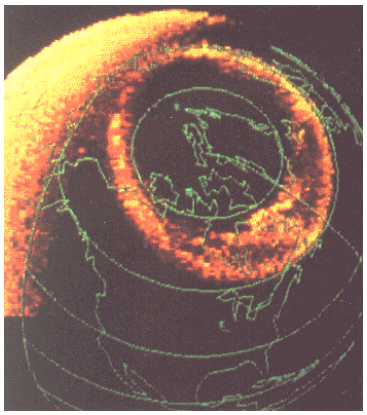

NASA - NASA image (US Govt) // http://www.phy6.org/Education/Figures/Grid_aur.gif

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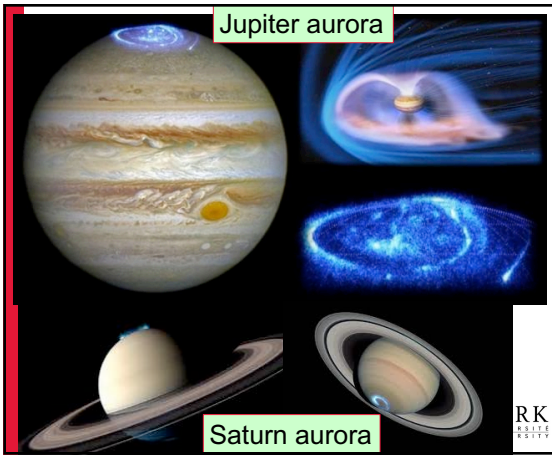
Jupiter aurora



Saturn aurora

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