Space Research Institute Graz
Austrian Academy of Sciences

Exploring the Planets and Moons in our Solar System

Helmut O. Rucker

CERN, Geneve, June 2006

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- The interplanetary medium, the solar wind and its interaction with magnetized planets

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The interplanetary medium, the solar wind and its interaction with magnetized planets

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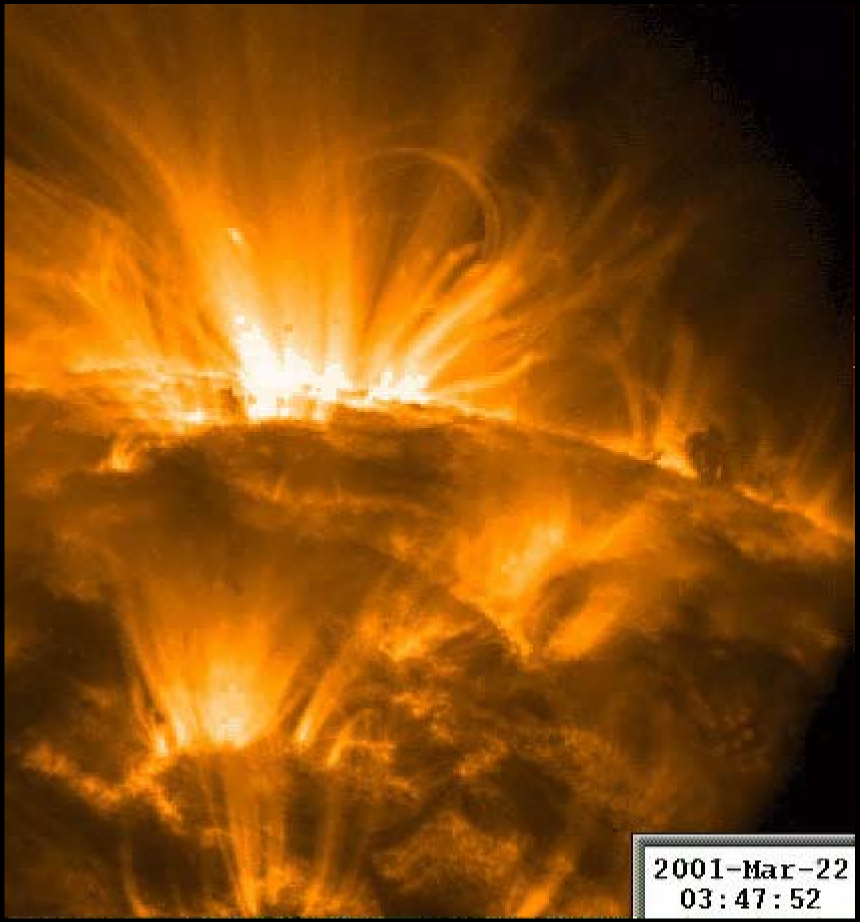
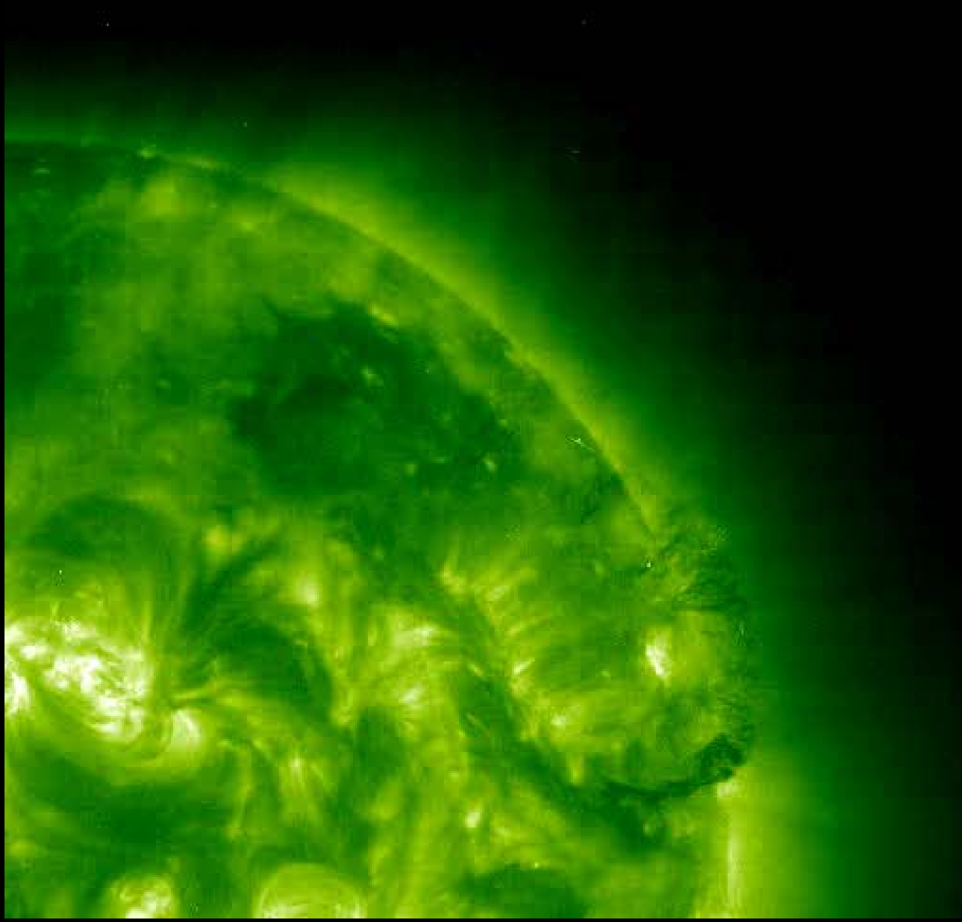
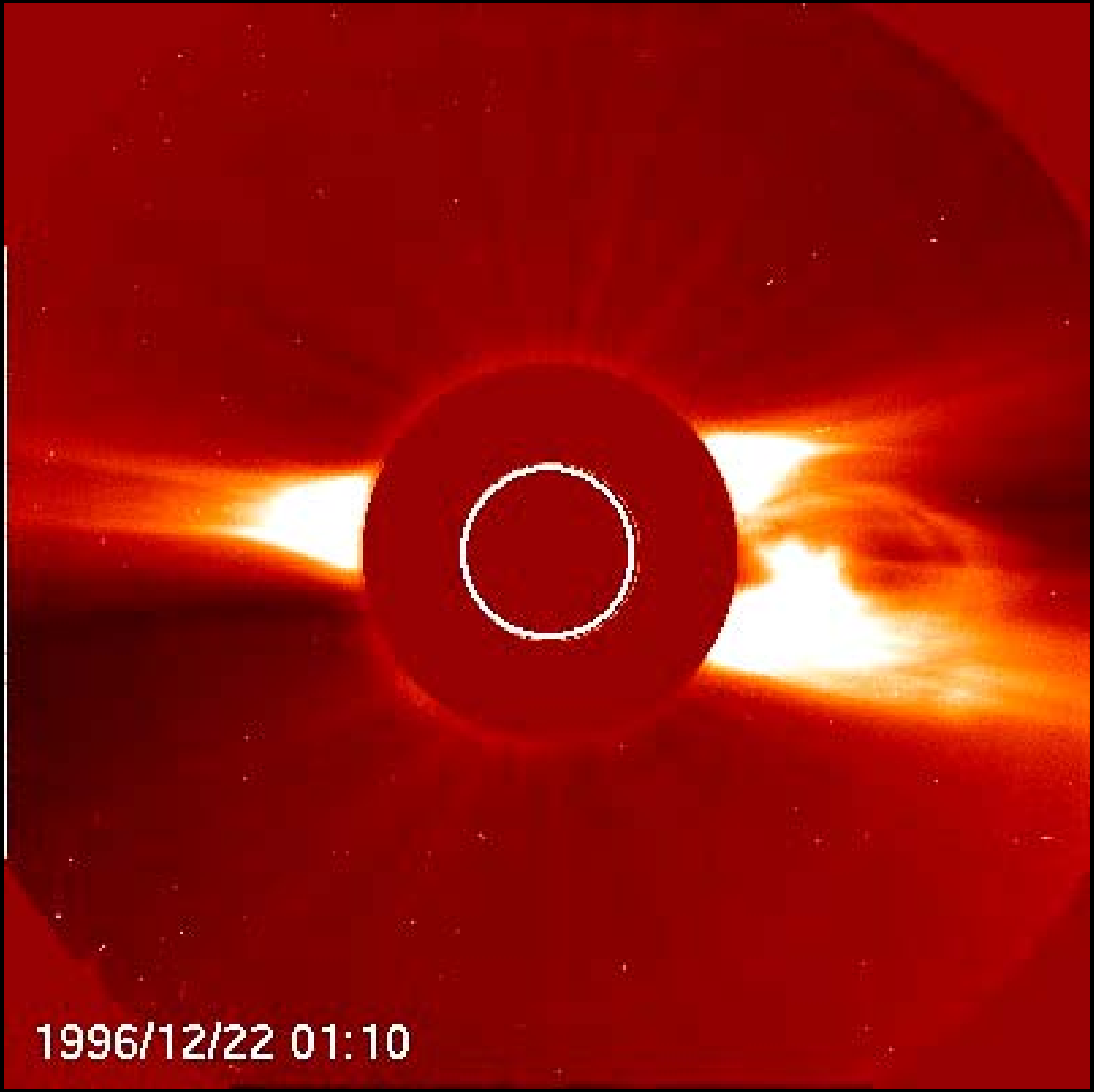
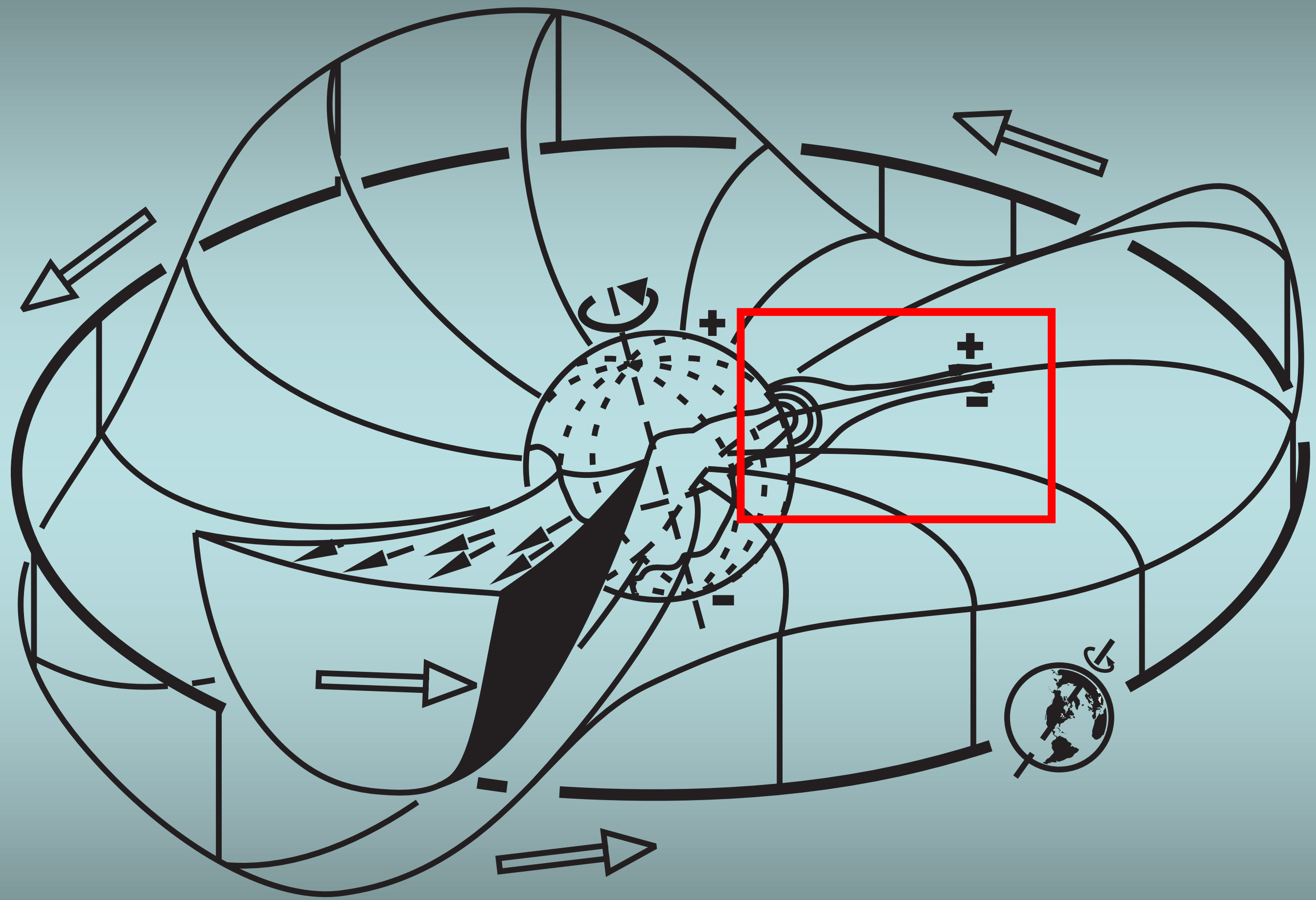
The central star of our solar system – the Sun







Mass loss by the expanding solar atmosphere, i.e. the solar wind:
~ 1 Mill. tons per second



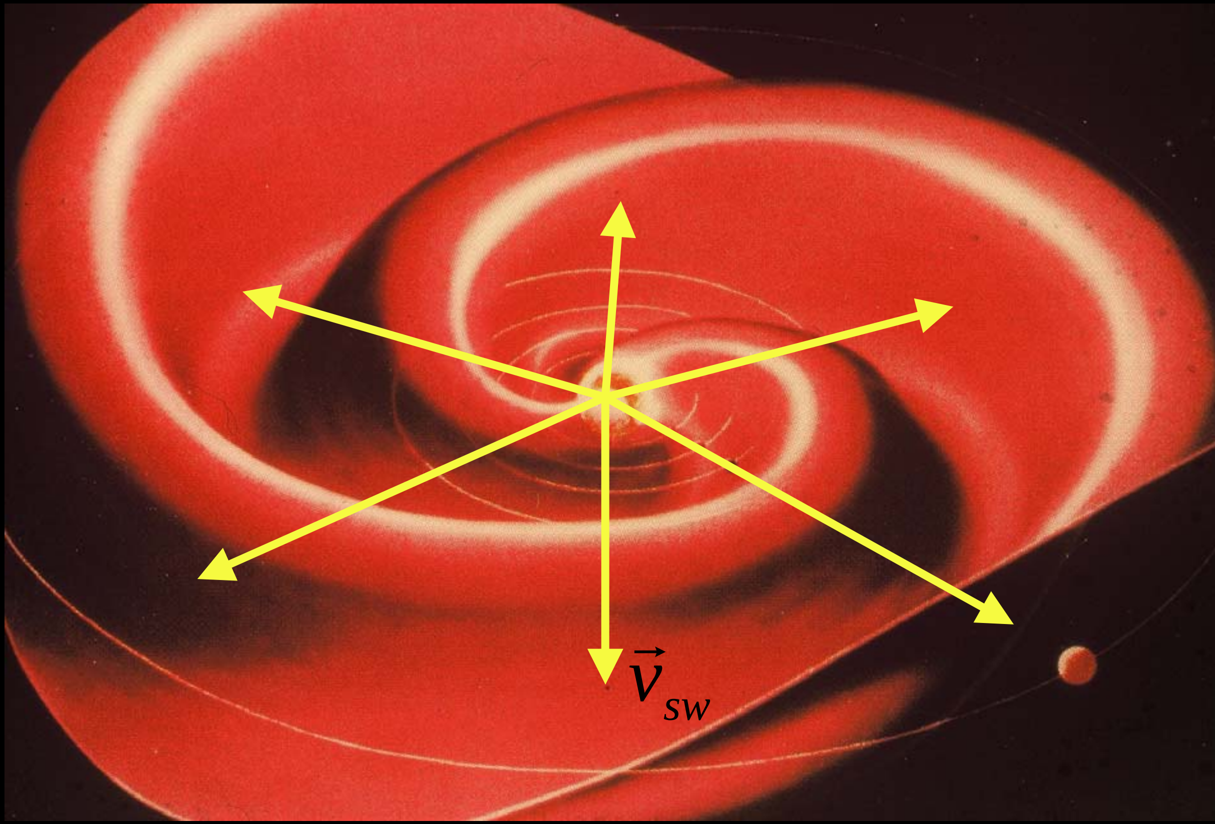
Viewgraph: Helmet streamer

The solar wind = expanding atmosphere of the Sun

highly conducting plasma,

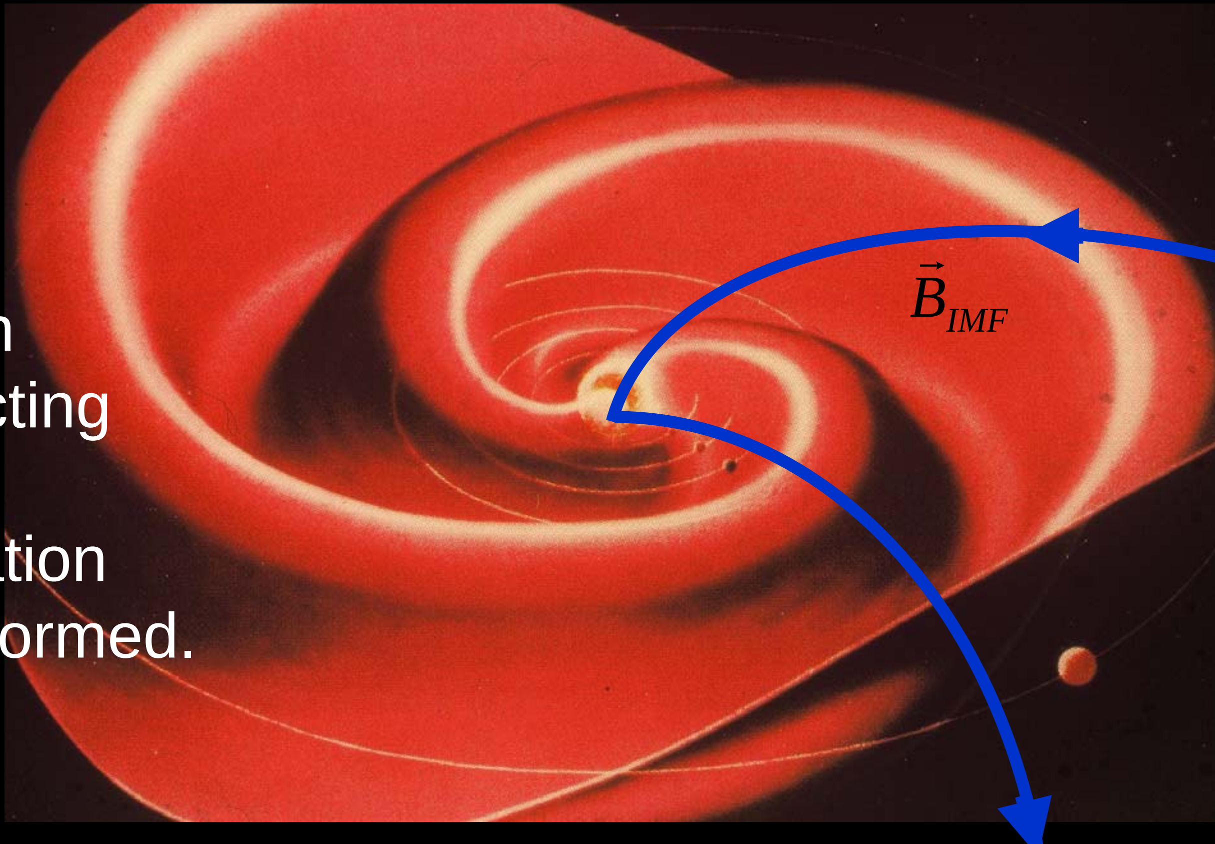
radially propagating

(300 km/s < v < 2000 km/s)



The solar wind = expanding atmosphere of the Sun
highly conducting plasma,
radially propagating
(300 km/s < v < 2000 km/s)

The interplanetary magnetic field is a solar magnetic field drawn out of the Sun by the highly conducting solar wind plasma.
Due to the solar rotation a spiral structure is formed.



Parker spiral:

$$\tan\Psi = \frac{\omega_{sun} r}{v_{sw}}$$

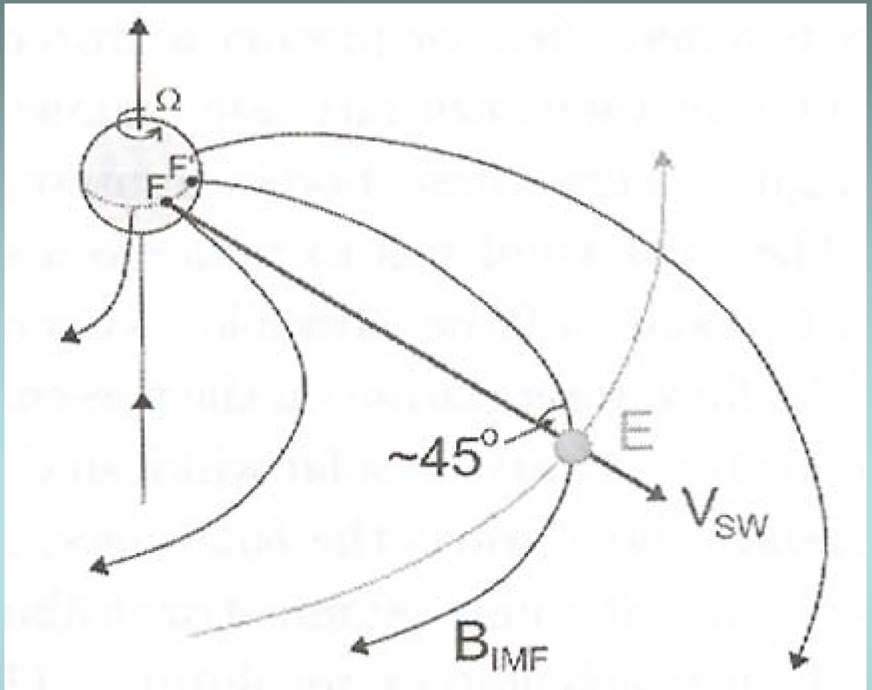
$$\omega_{sun} = 2\pi/(25.38 \times 86{,}400 s)$$

$$\omega_{sun} = 2.86 \times 10^{-6} s^{-1}$$

$$v_{sw} = 450 km s^{-1}$$

$$\psi(r = 1.0 AU) = 43.6°$$

$$\psi(r = 9.5 AU) = 83.7°$$



At:	Angle:	Strength:
Mercury	21°	35 nT
Earth	45°	7 nT
Mars	56°	4 nT
Jupiter	80°	1 nT
Neptune	88°	0.2 nT

Solar wind average properties at r ~ 1 AU:

Proton density	$6.6\ cm^{-3}$
Electron density	$7.1\ cm^{-3}$
He^{2+} density	$0.25\ cm^{-3}$

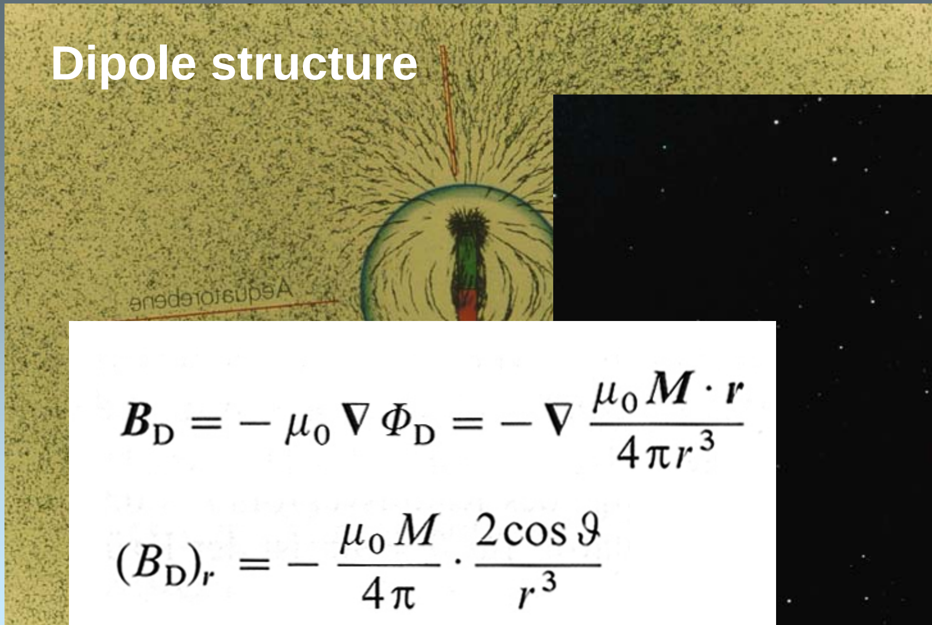
Different types of solar wind (sw):

Fast sw:	400 < v < 800 km/s,	Helium 3 – 4 %
Slow sw of minimum type:	250 < v < 400 km/s,	Helium < 2 %
Slow sw of maximum type:	250 < v < 400 km/s,	Helium ~ 4 %
Coronal mass ejections (CMEs):	400 < v < 2000 km/s,	Helium(++) ~ 30 %

Solar wind average properties at r ~ 1 AU:

Proton density	$6.6\ \mathrm{cm}^{-3}$
Electron density	$7.1\ \mathrm{cm}^{-3}$
He^{2+} density	$0.25\ \mathrm{cm}^{-3}$
Flow speed ($\sim$ radial)	$450\ \mathrm{km\ s}^{-1}$
Proton temperature	1.2×10^5 K
Electron temperature	1.4×10^5 K
Magnetic field strength	7 nT
Sonic Mach number	2–10
Alfvén Mach number	2–10
Mean free path	~ 1 AU

Dipole structure



$$\boldsymbol{B}_{\mathrm{D}} = -\mu_0 \nabla \Phi_{\mathrm{D}} = -\nabla \frac{\mu_0 \boldsymbol{M} \cdot \boldsymbol{r}}{4\pi r^3}$$

$$(B_{\mathrm{D}})_r = -\frac{\mu_0 M}{4\pi} \cdot \frac{2\cos\vartheta}{r^3}$$

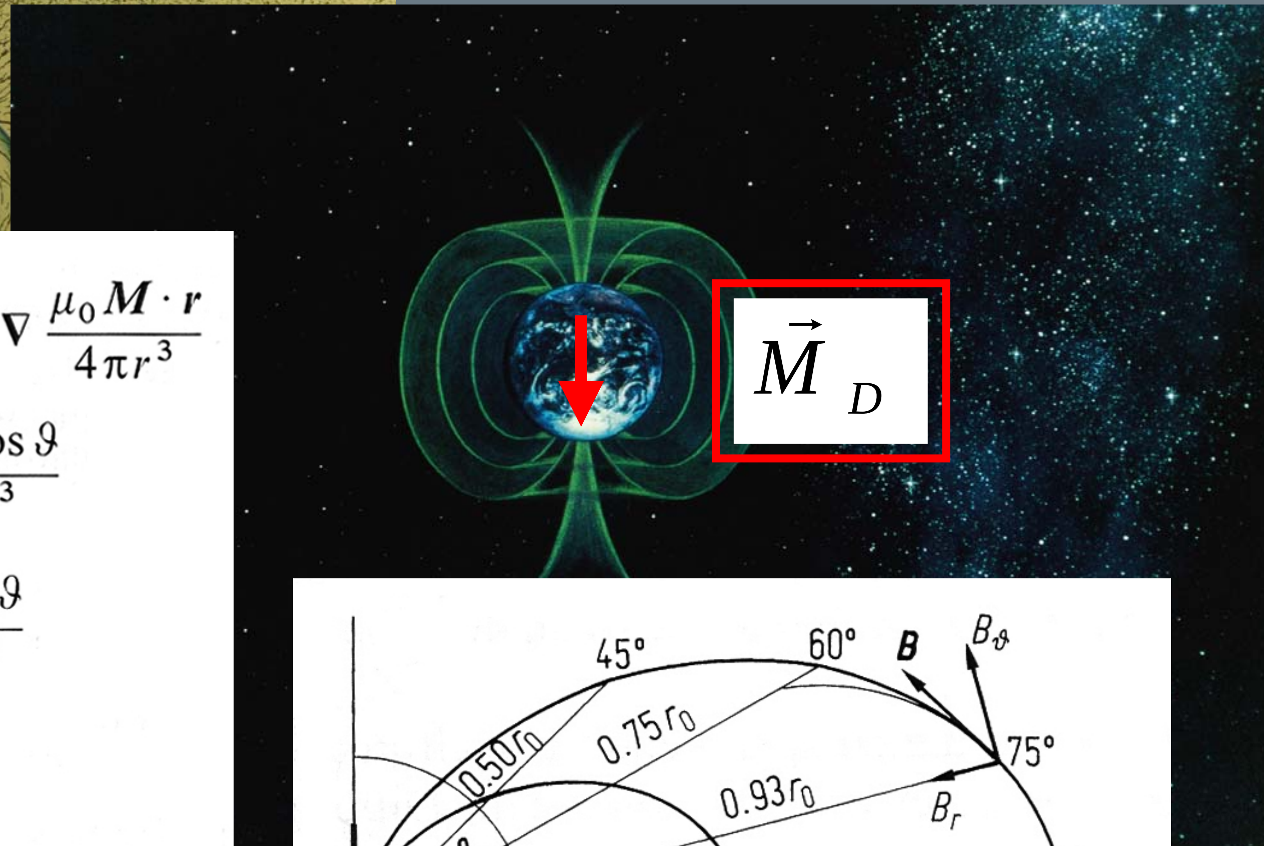
$$(B_{\mathrm{D}})_\vartheta = -\frac{\mu_0 M}{4\pi} \cdot \frac{\sin\vartheta}{r^3}$$

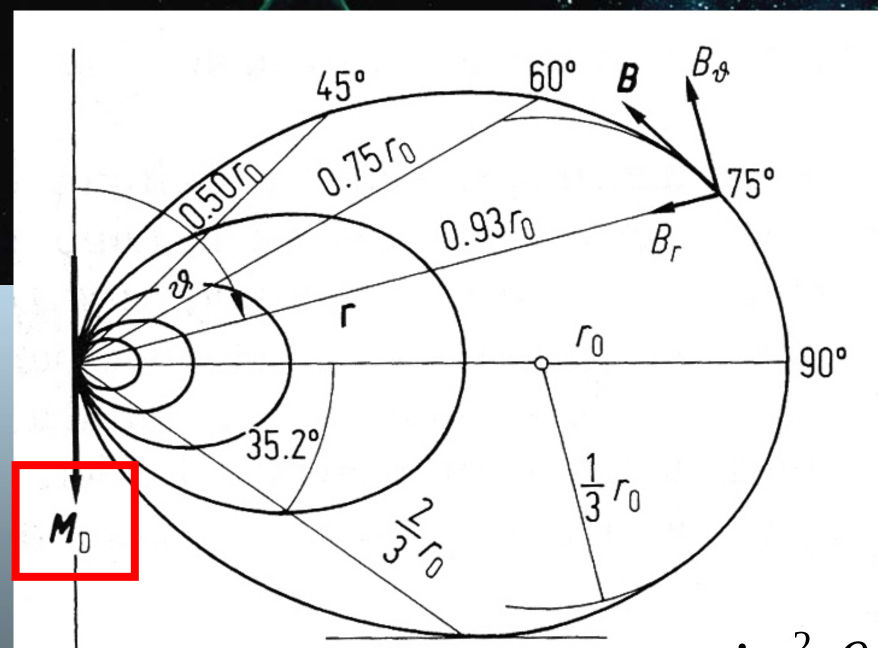
$$(B_{\mathrm{D}})_\phi = 0$$

$$B(r,\vartheta) = \sqrt{B_r^2 + B_\vartheta^2}$$

$$B(r,\vartheta) = \frac{\mu_0 M}{4\pi r^3}\sqrt{1 + 3\cos^2\vartheta}$$

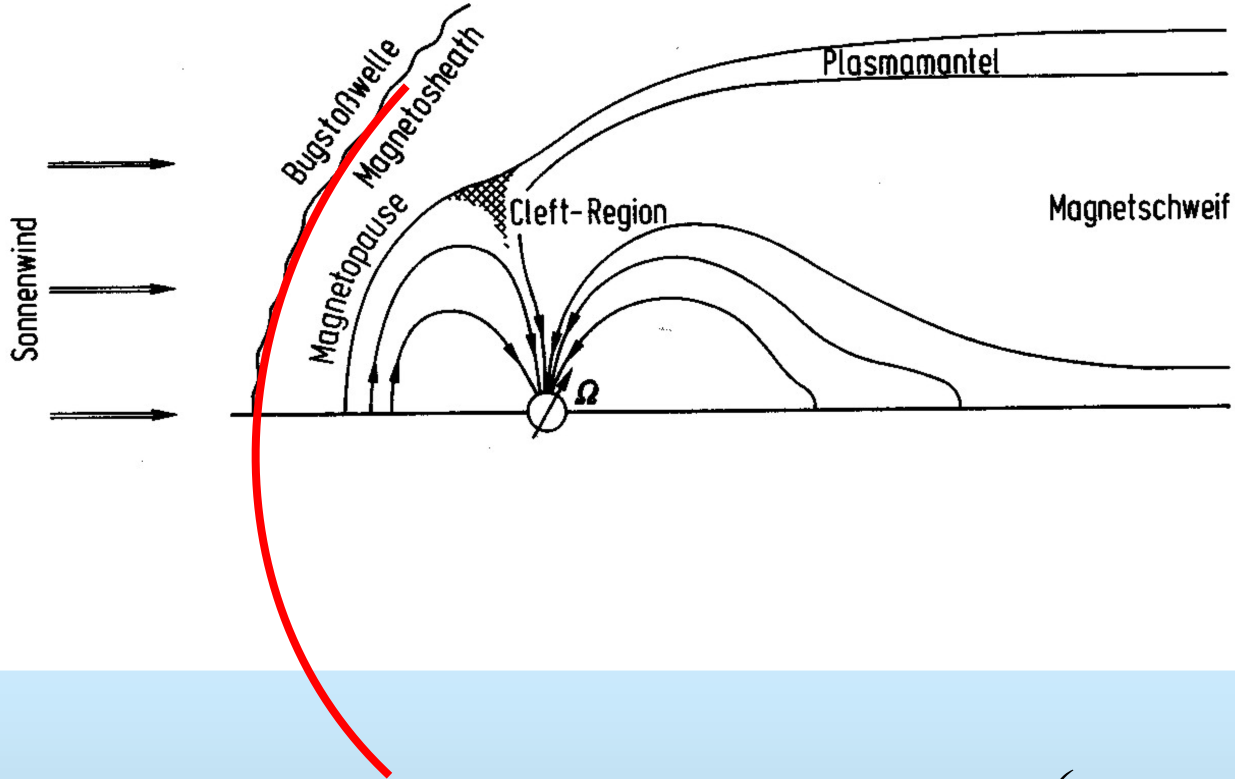
$$B_{\text{Äquator}} = \frac{\mu_0 M}{4\pi r^3} = B_0 \left(\frac{r_{\mathrm{E}}}{r}\right)^3$$





$$r = r_0 \sin^2 \vartheta$$

Interaction between the solar wind and planetary magnetic field



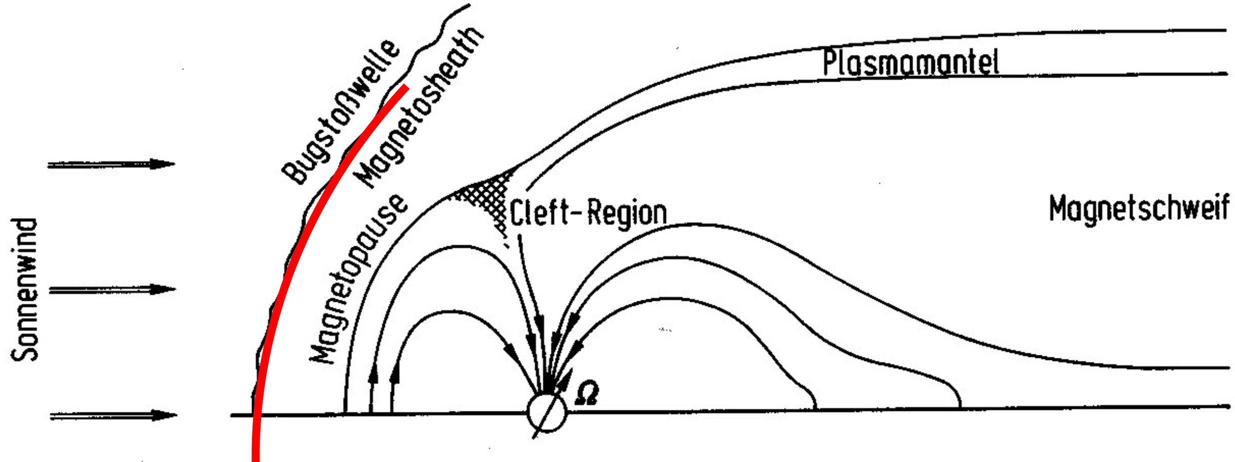
Solar wind bulk flow = super-sonic flow

$$v_{sonic} = \left(\frac{c_p}{c_V} \frac{nk(T_e + T_i)}{nm} \right)^{\frac{1}{2}}$$

= super-Alfvenic flow

$$v_A = \frac{B}{\sqrt{\mu_0 \rho}}$$

Interaction between the solar wind and planetary magnetic field



Bow shock:

Transition of solar wind plasma described by the Rankine Hugoniot equations.
Change after transition:

bulk speed ↓
particle density ↑
plasma pressure ↑
plasma temperature ↑

$$[\rho u_{\mathrm{n}}] = 0\,,$$

$$\left[\rho u_{\mathrm{n}}^2 + P + \frac{B^2}{2\mu_0}\right] = 0\,,$$

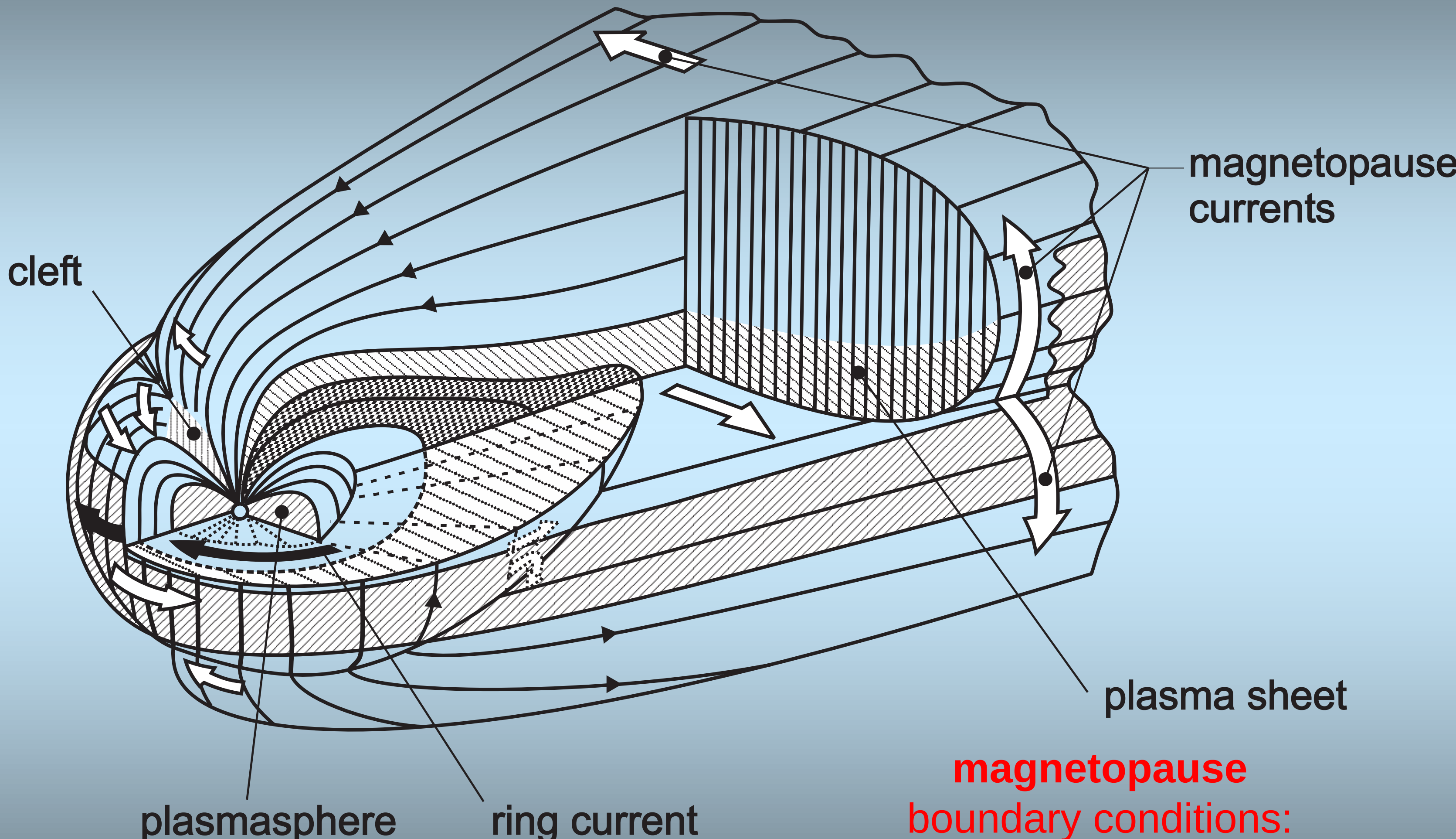
$$\left[\rho u_{\mathrm{n}}^2 \mathbf{u}_{\mathrm{t}} - \frac{B_{\mathrm{n}}}{\mu_0}\mathbf{B}_{\mathrm{t}}\right] = 0\,,$$

$$\left[\rho u_{\mathrm{n}}^2 \left(\frac{1}{2}u^2 + \frac{\gamma}{\gamma - 1}\frac{P}{\rho}\right) + \mu_{\mathrm{n}}\frac{B^2}{\mu_0} - \mathbf{u}\cdot\mathbf{B}\frac{B_{\mathrm{n}}}{\mu_0}\right] = 0\,,$$

$$[B_{\mathrm{n}}] = 0\,,$$

$$[u_{\mathrm{n}}\mathbf{B}_{\mathrm{t}} - B_{\mathrm{n}}\mathbf{u}_{\mathrm{t}}] = 0\,,$$

3D schematics of the terrestrial magnetosphere

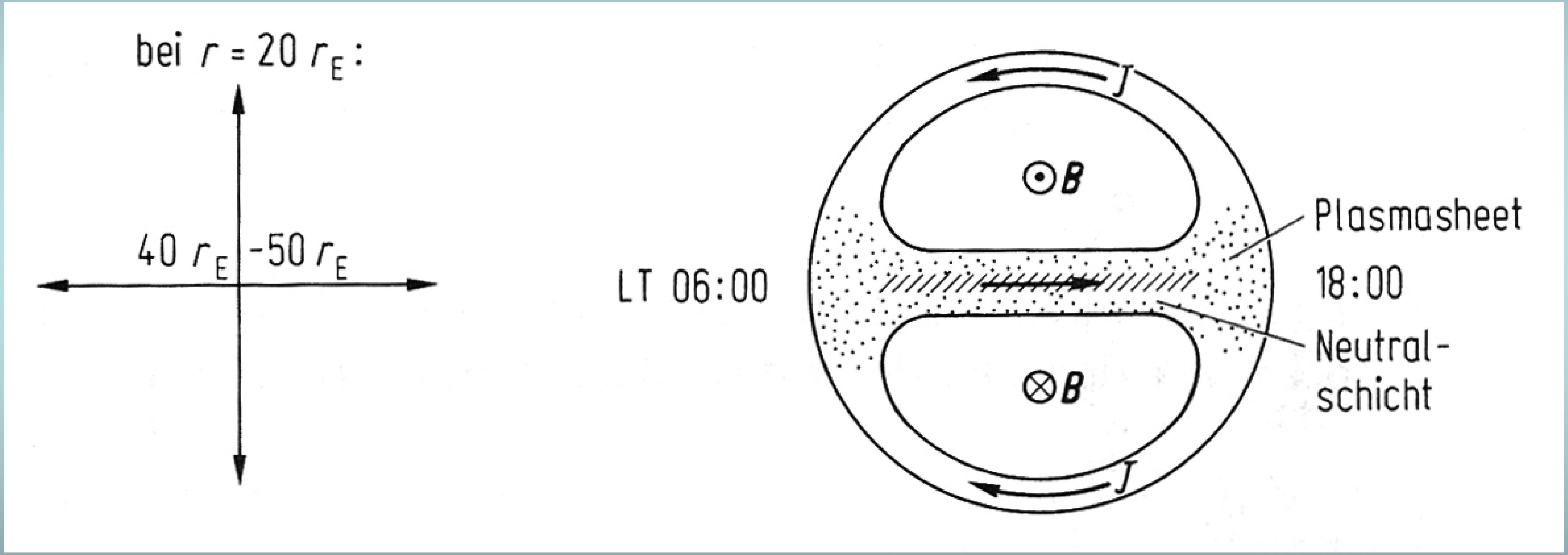


magnetopause
boundary conditions:

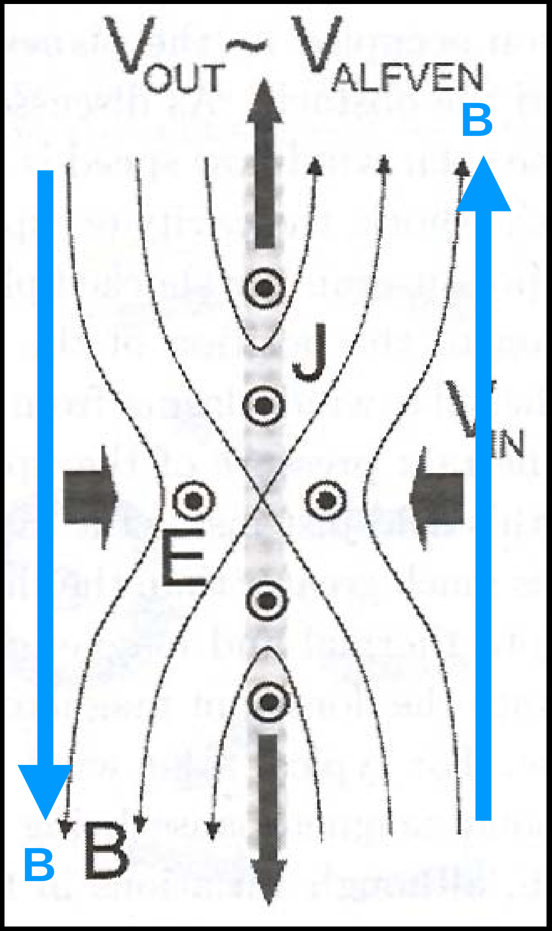
$$nmv^2 \cos^2\alpha = B^2 / 2\mu_0$$

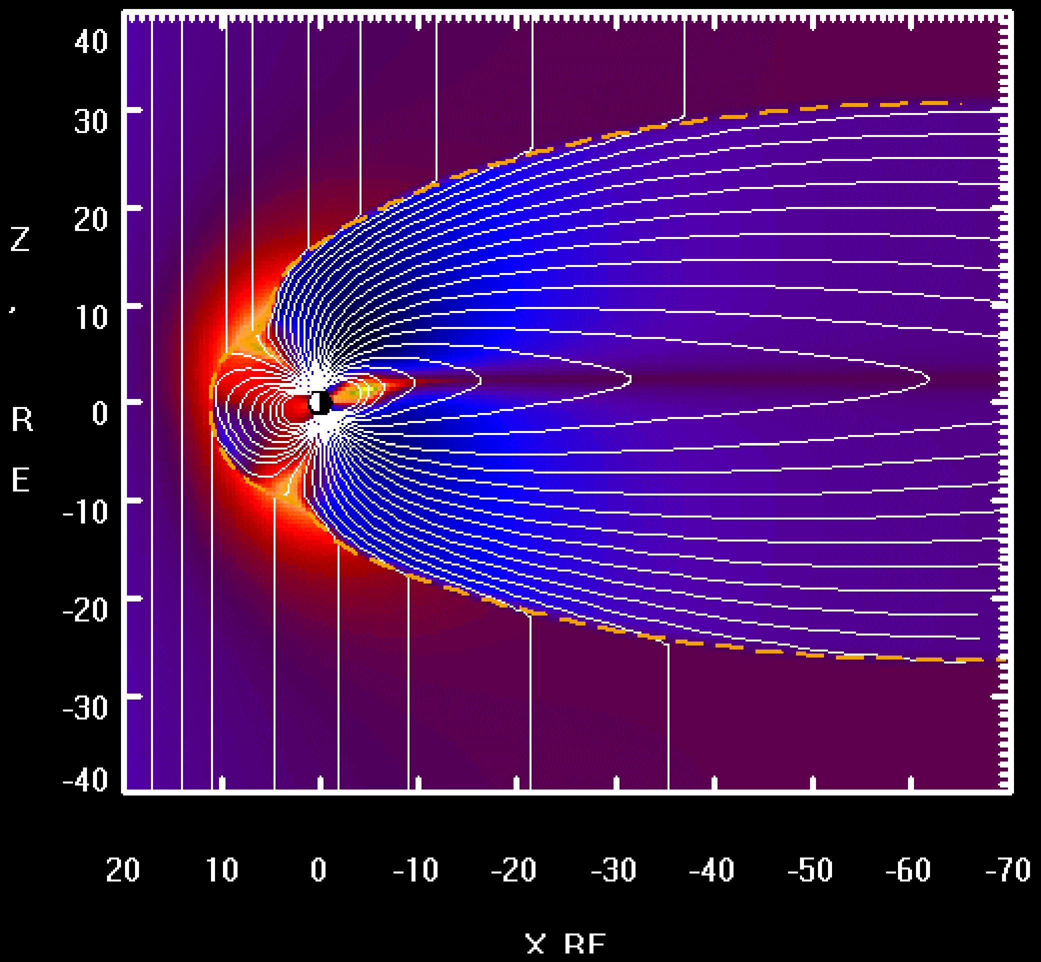
$$B_n = 0$$

Magnetotail cross section at r = 20 Re

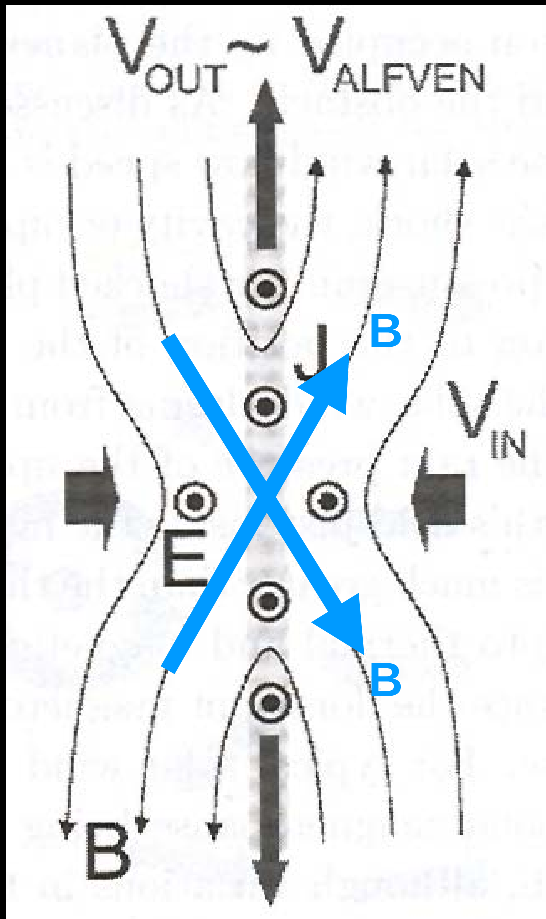


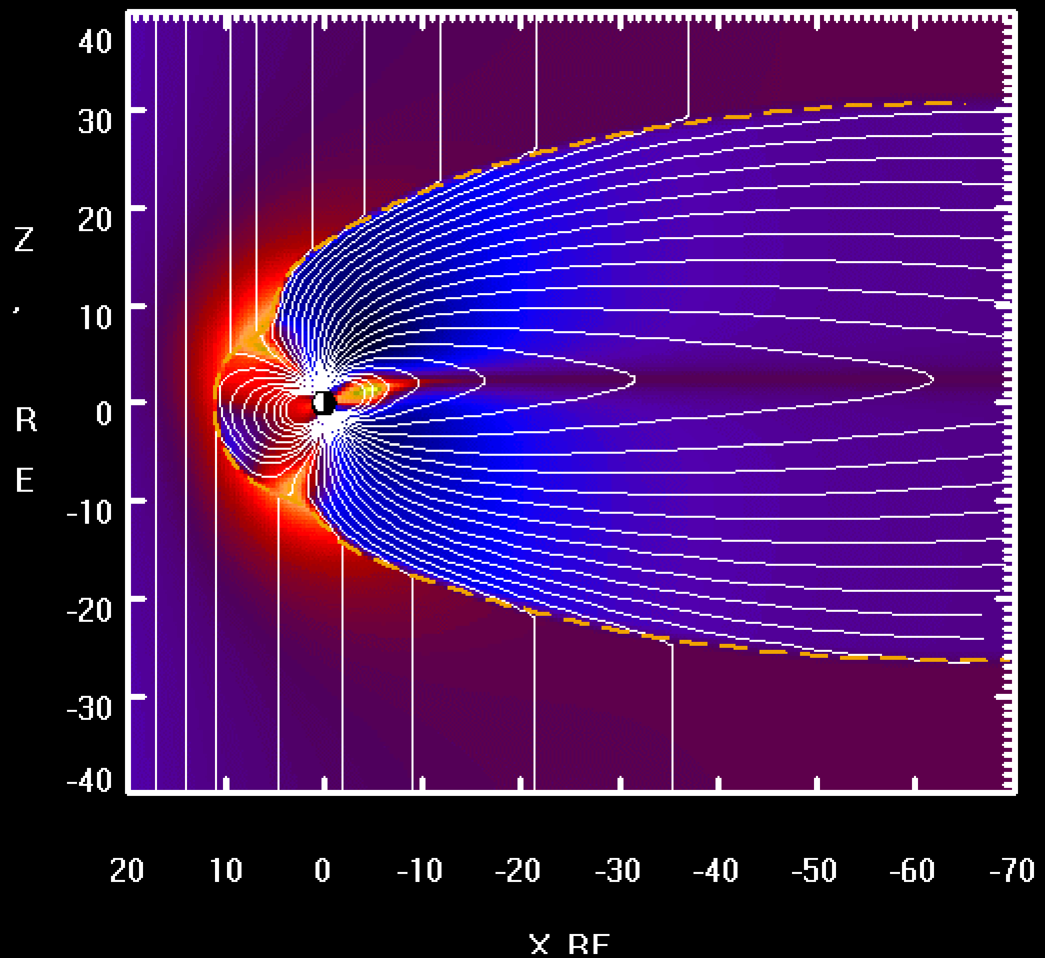
Magnetic reconnection



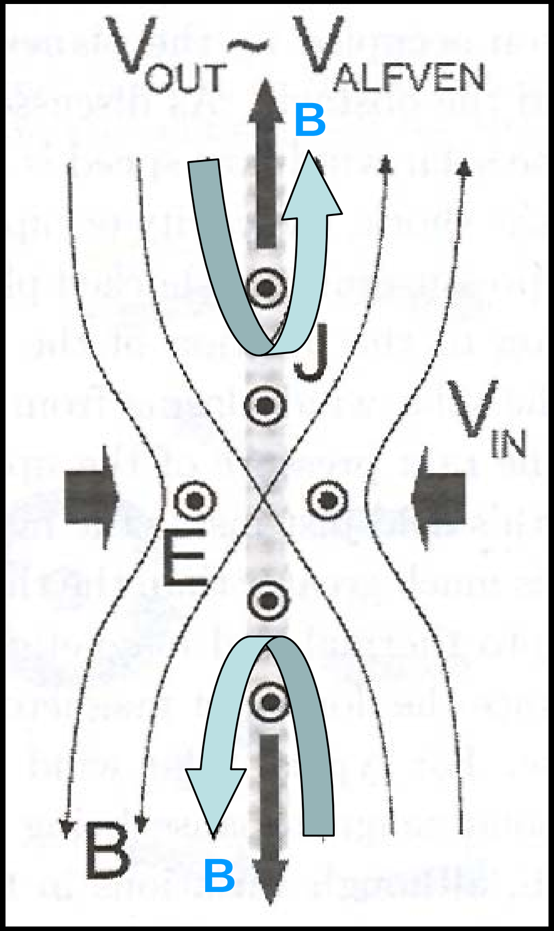


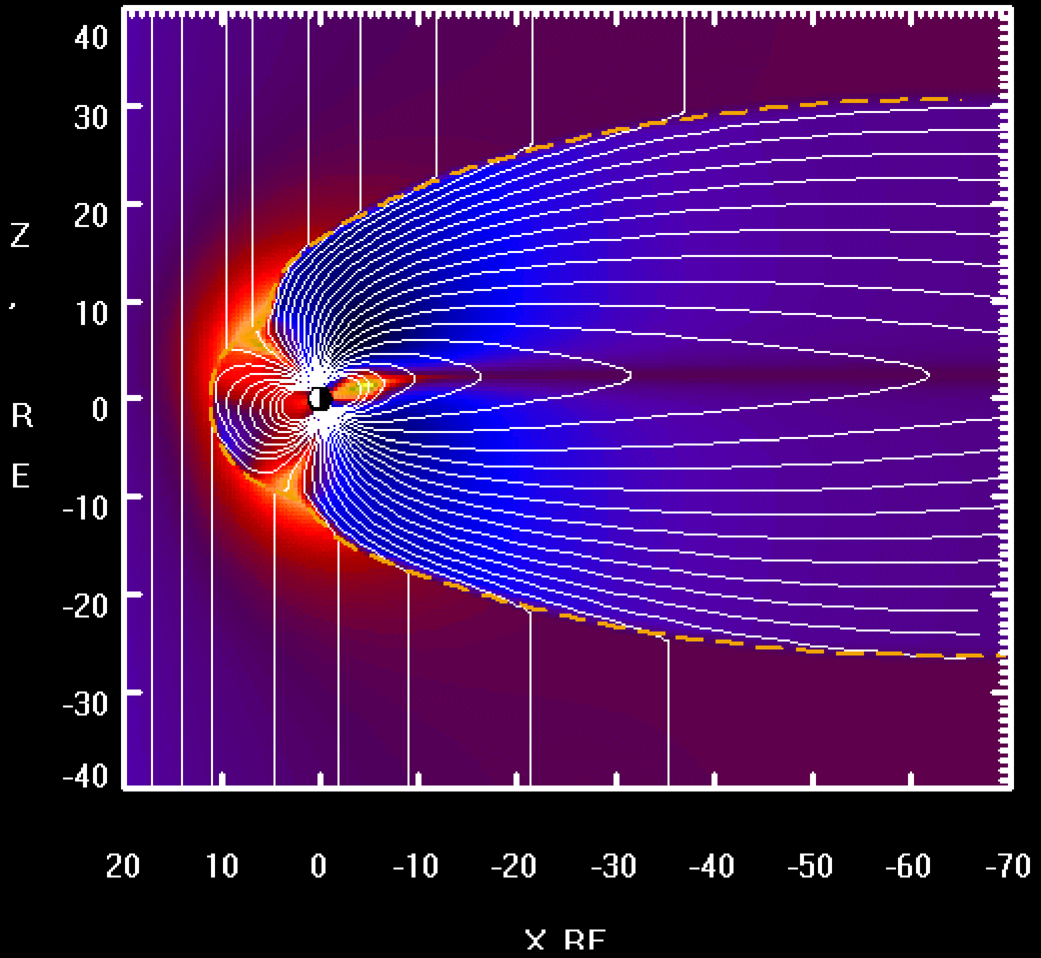
Magnetic reconnection

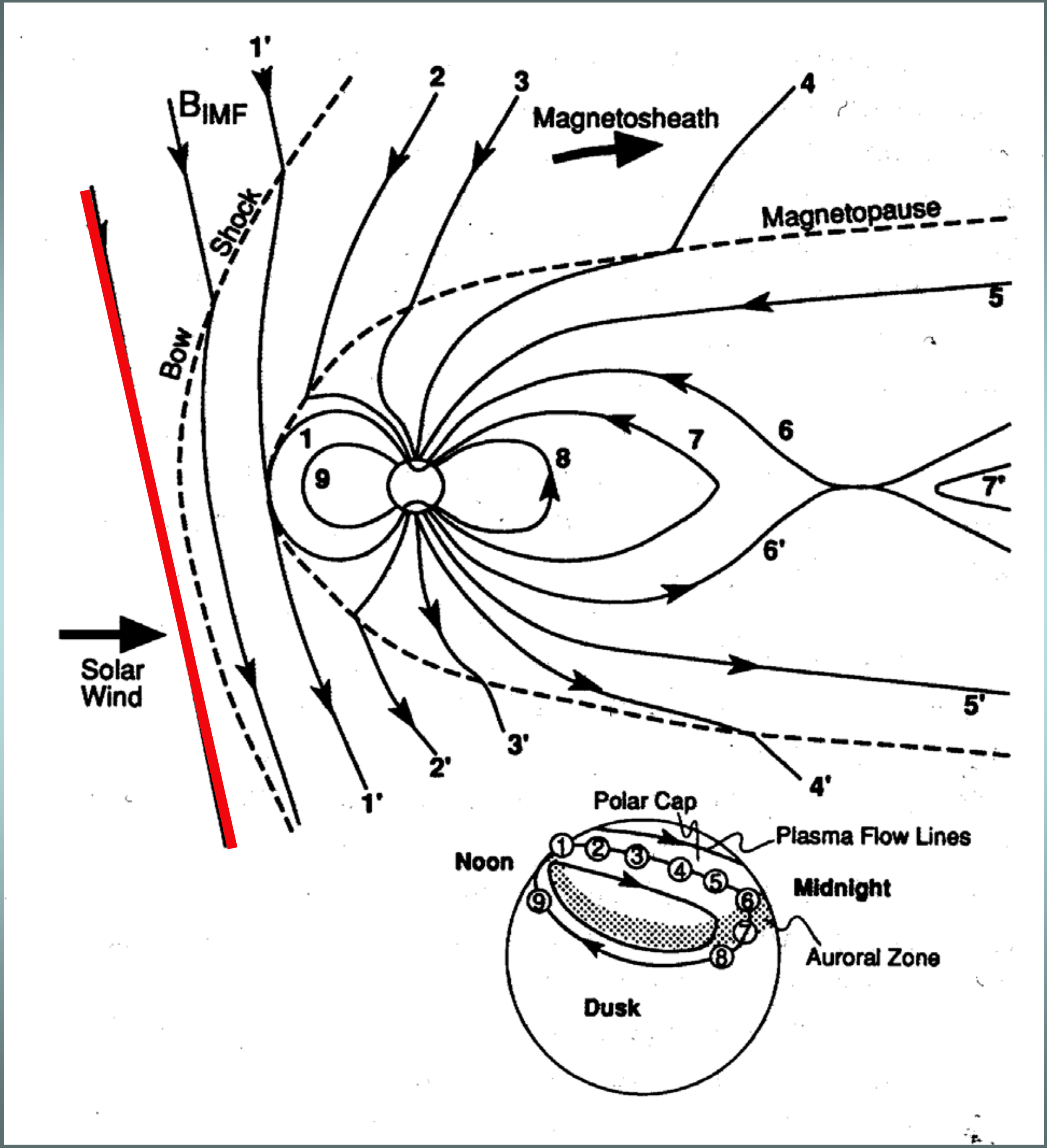




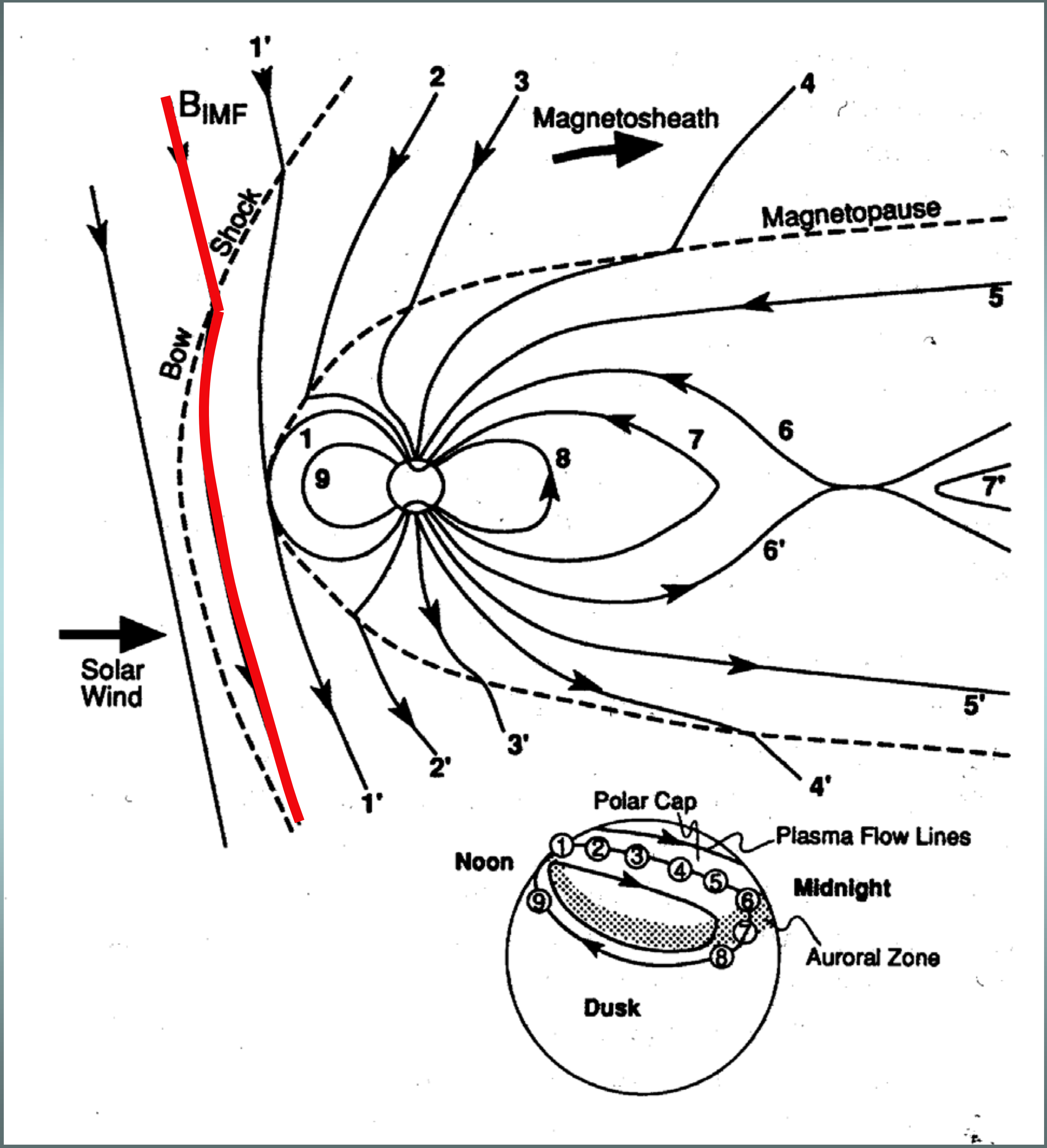
Magnetic reconnection





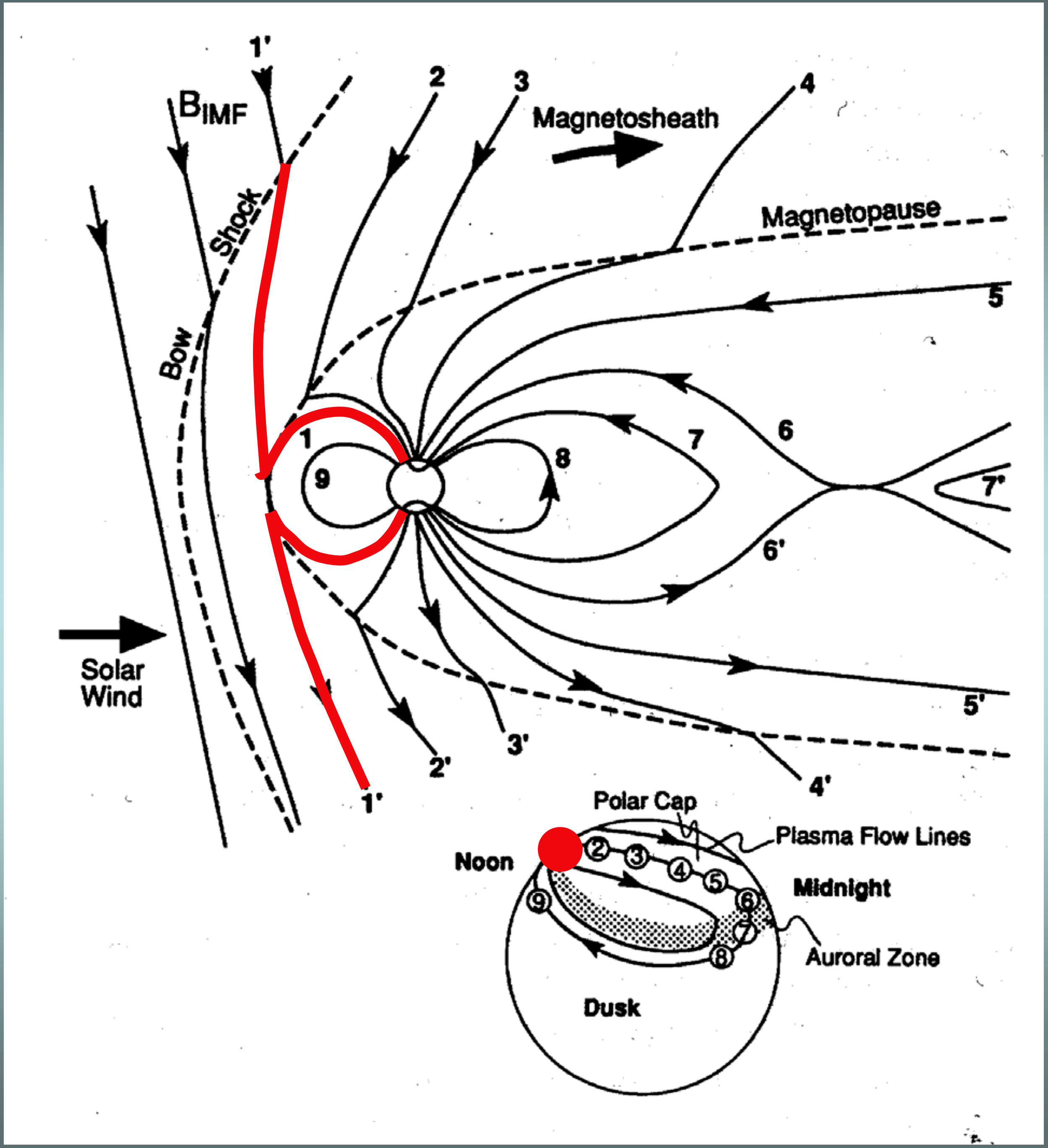


Courtesy Prange, 2006



Courtesy Prange, 2006

1st reconnection = start of the cycle



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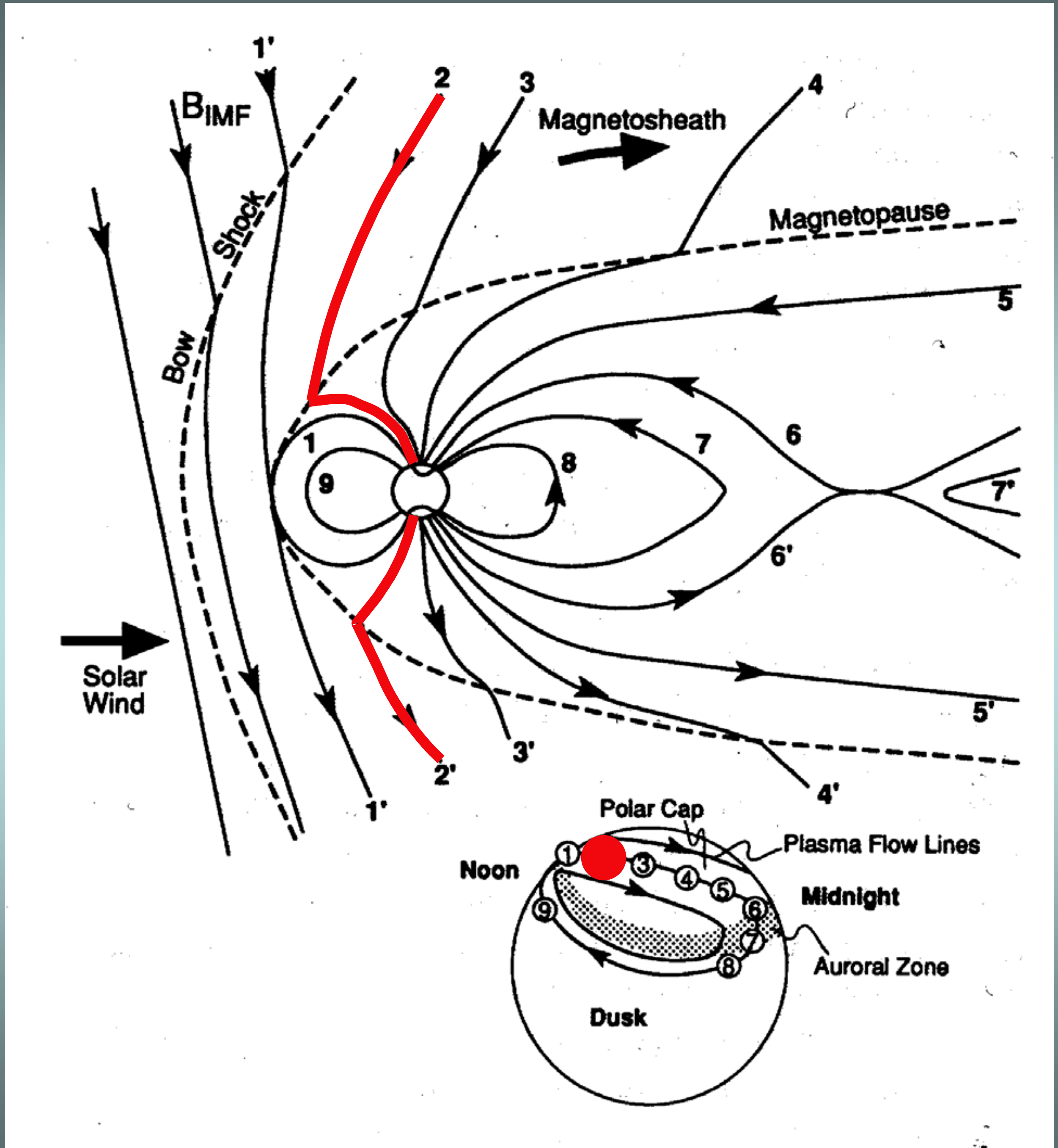

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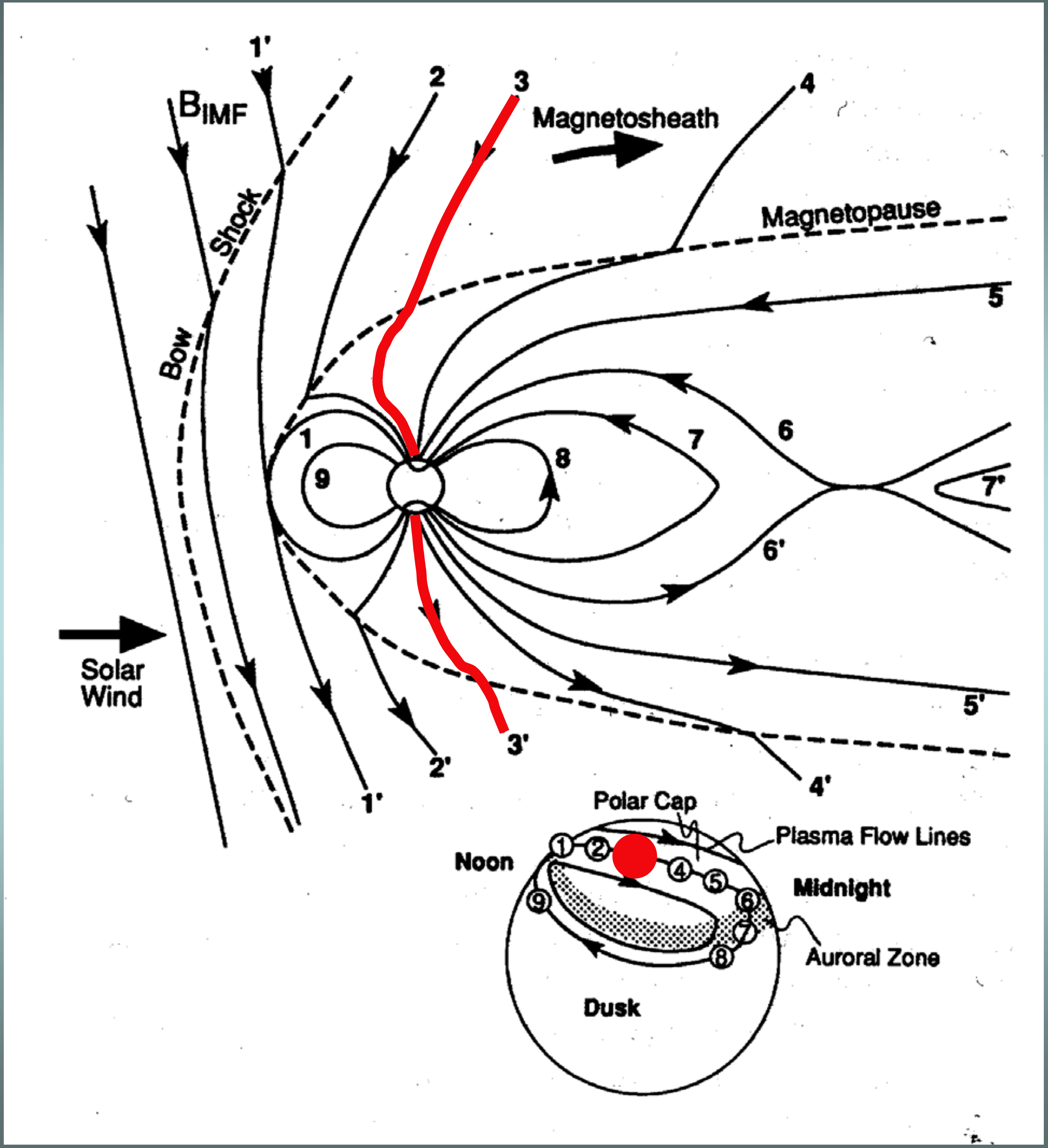
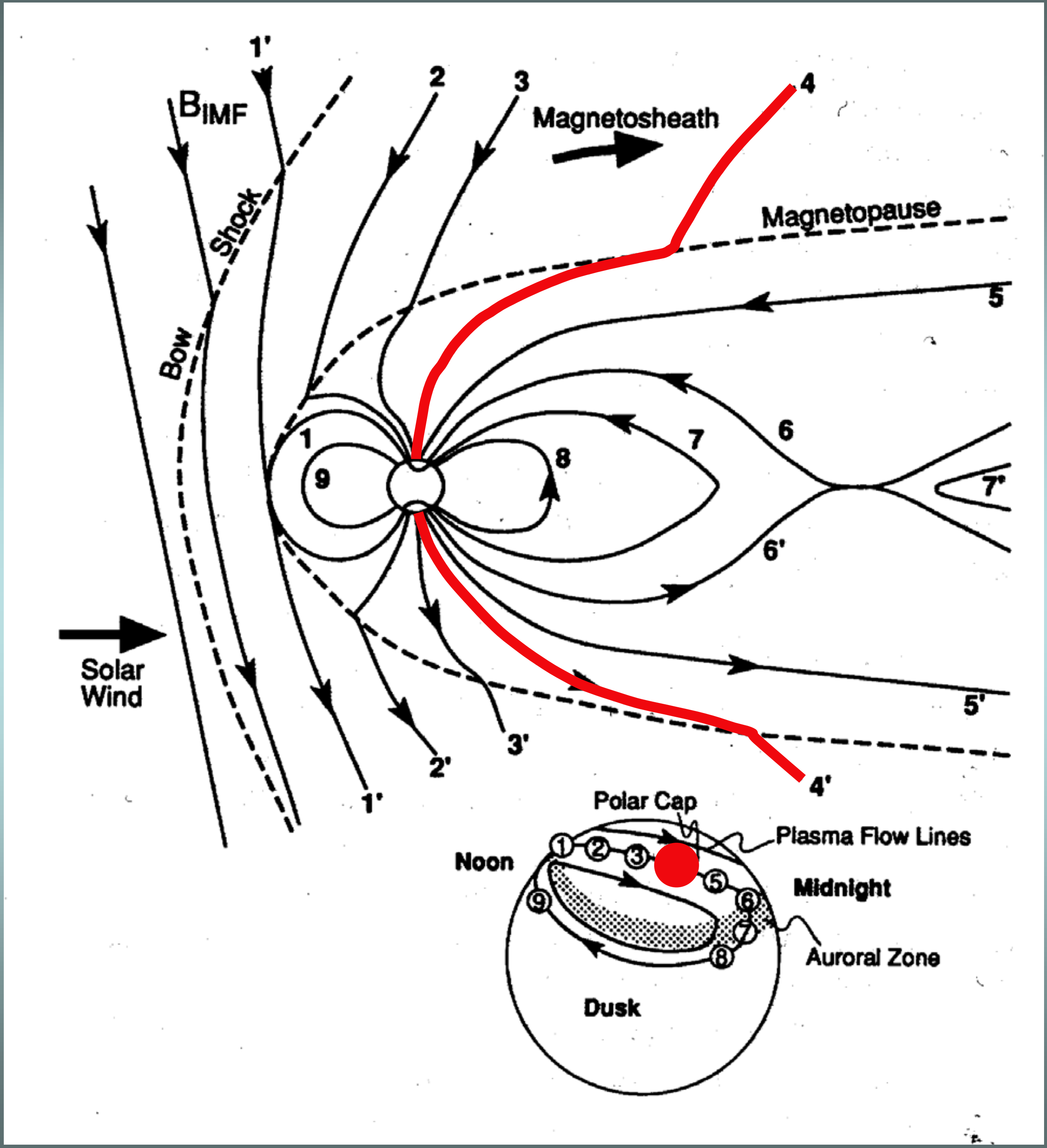


Courtesy Prange, 2006

transport over the poles



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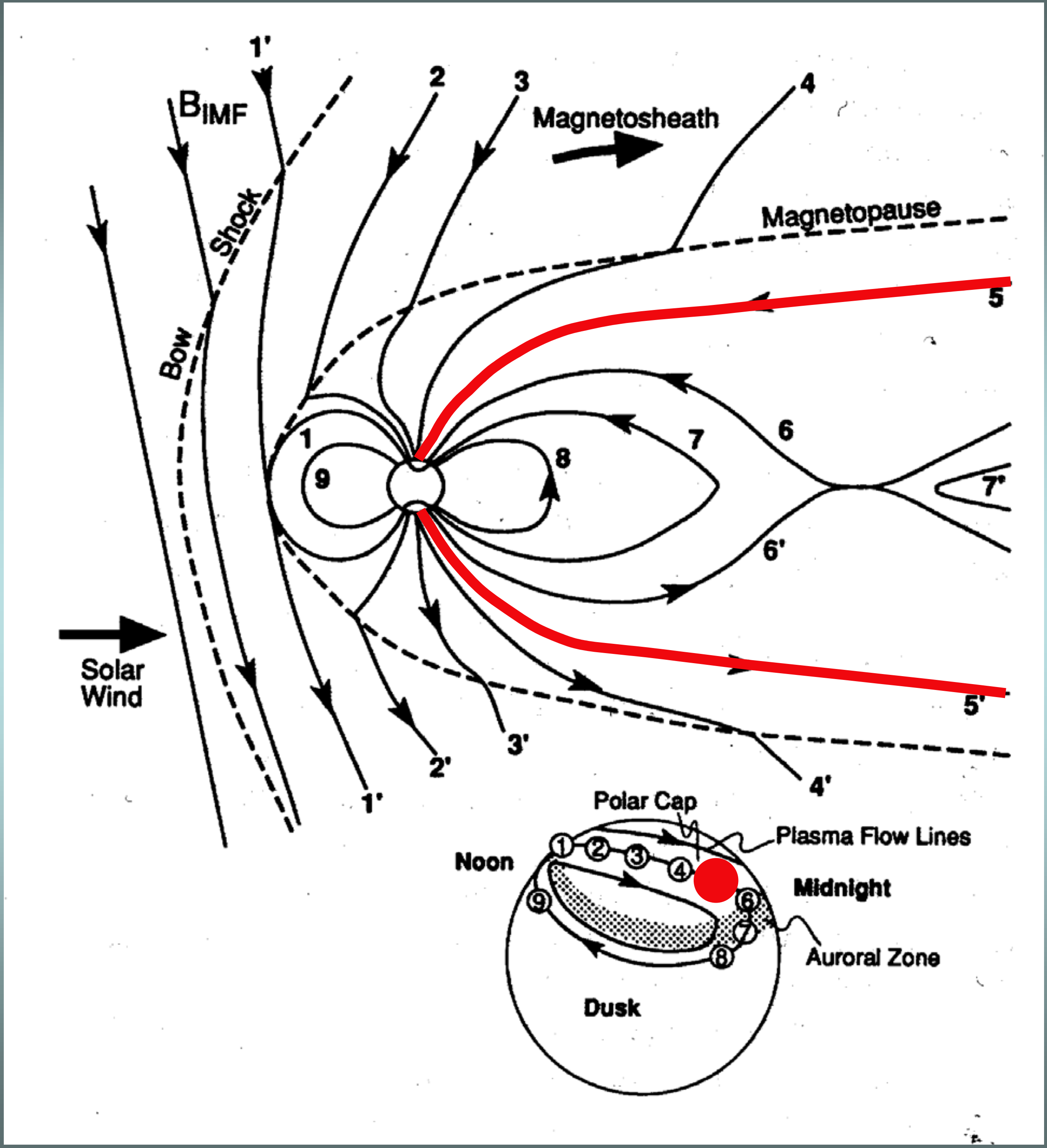
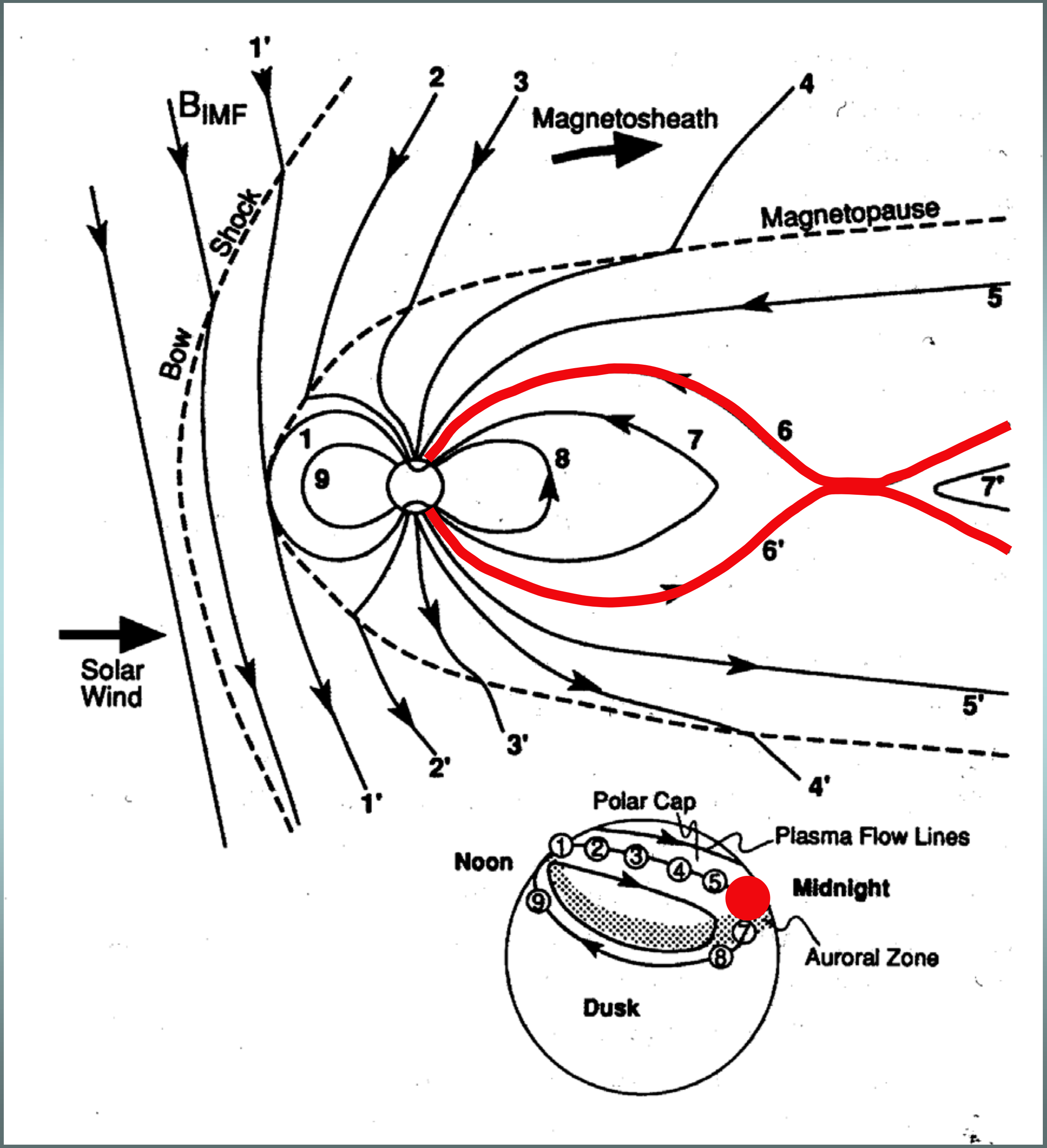


Courtesy Prange, 2006

2nd reconnection



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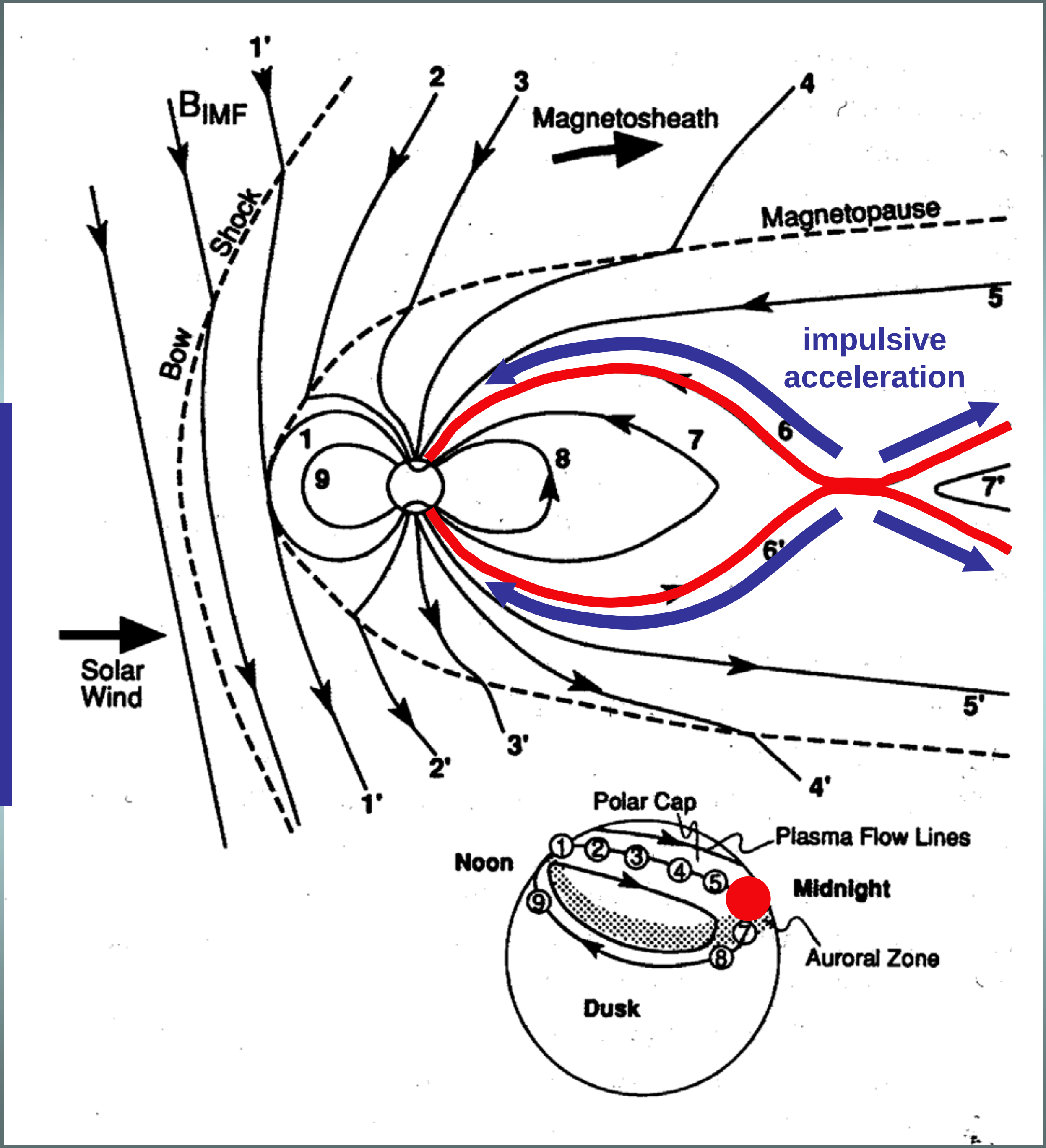
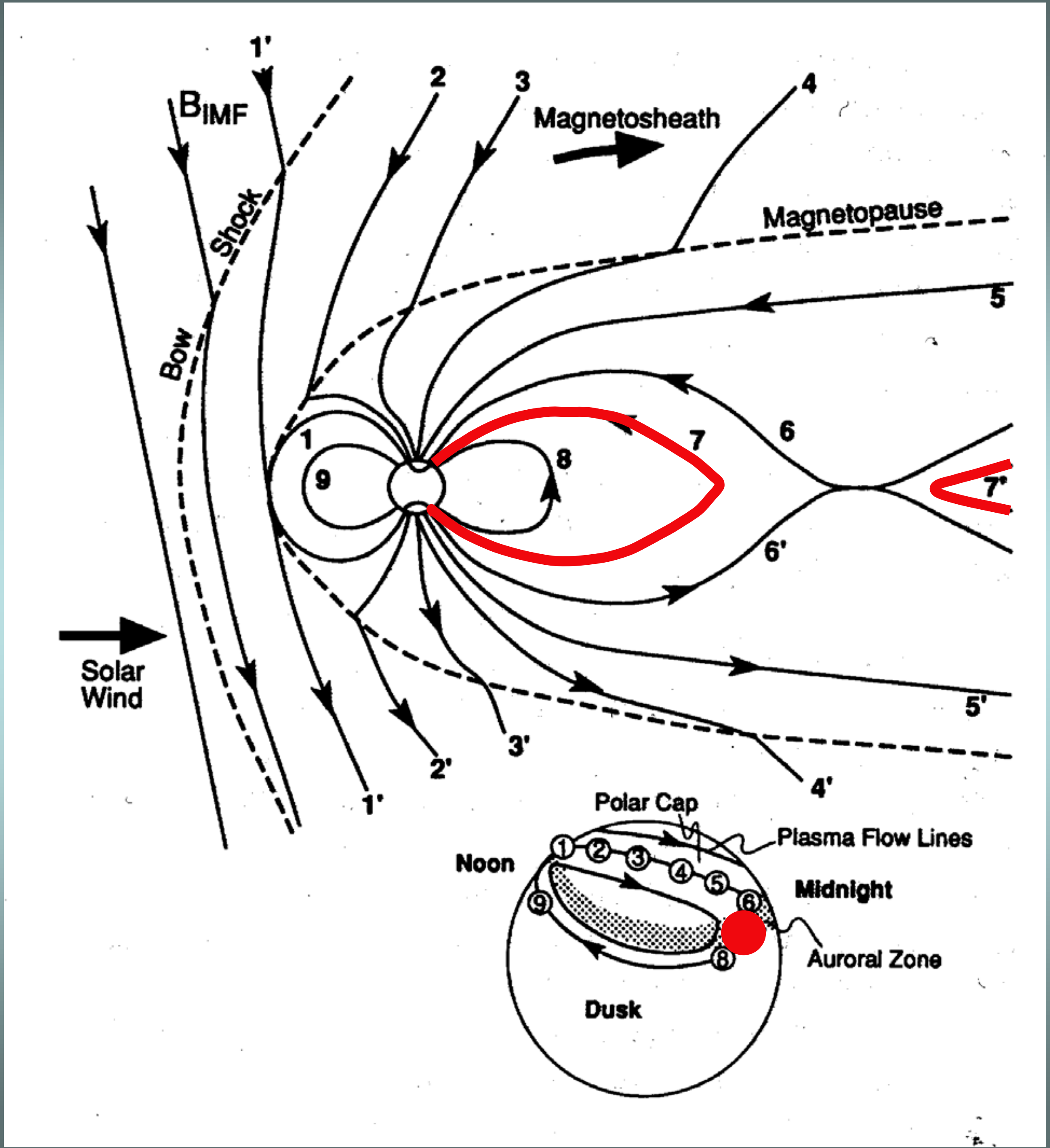
Release of energy (the stretched configuration contains additional energy to accelerate plasma)



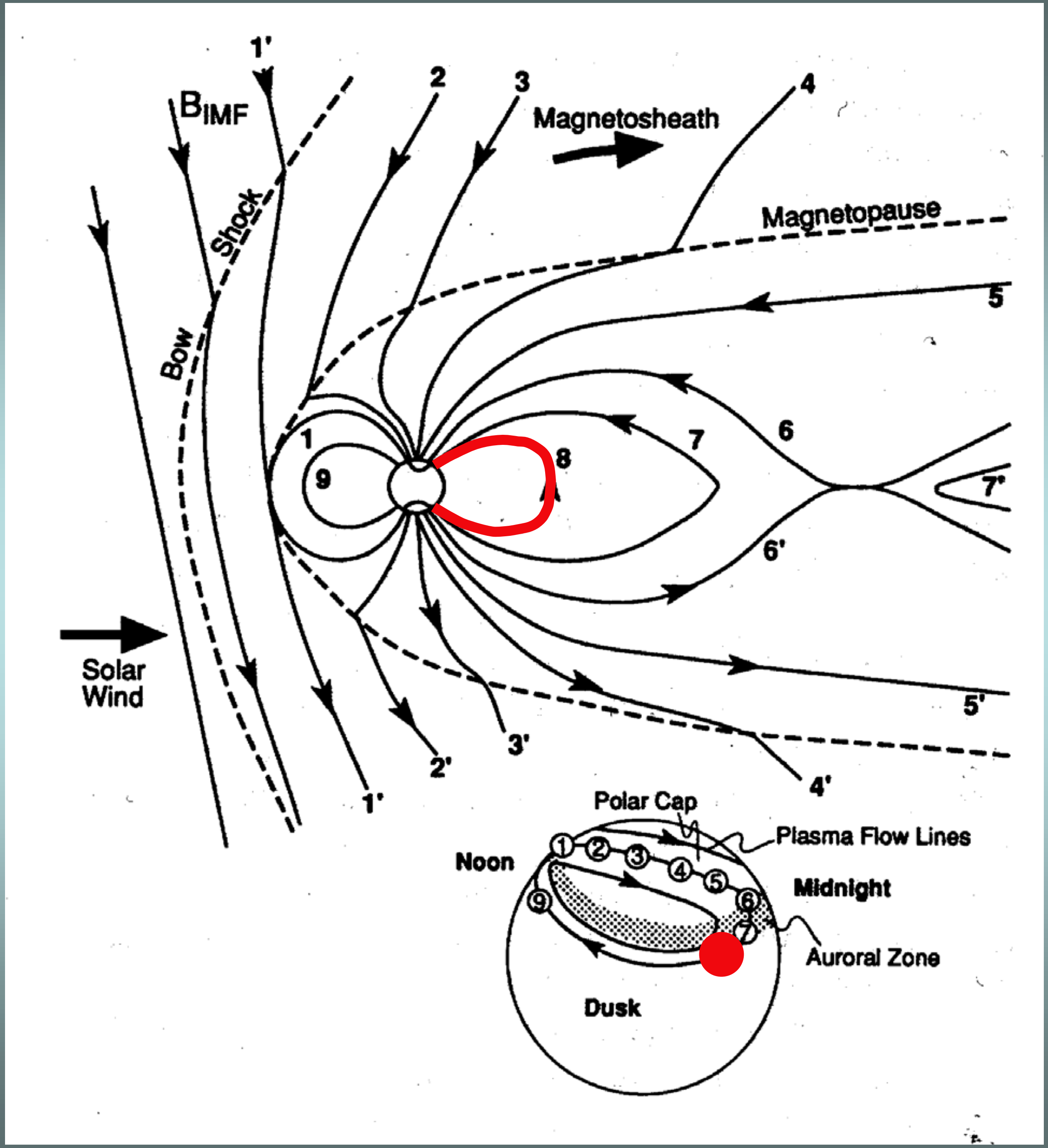
Courtesy Prange, 2006

ejection of plasma into the magnetotail

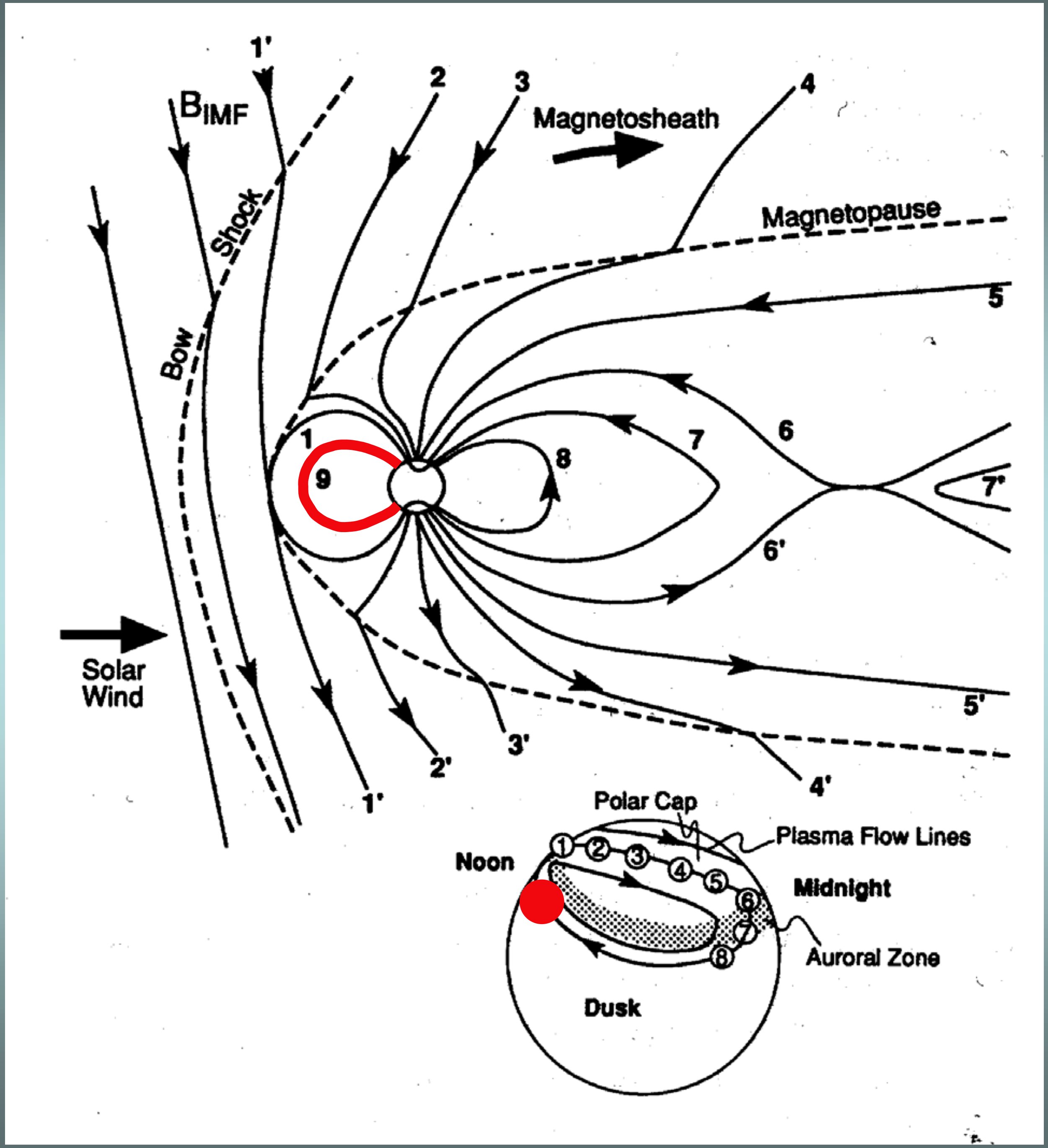


Courtesy Prange, 2006

returning of a
« magnetic loop »
back to the dayside



Courtesy Prange, 2006



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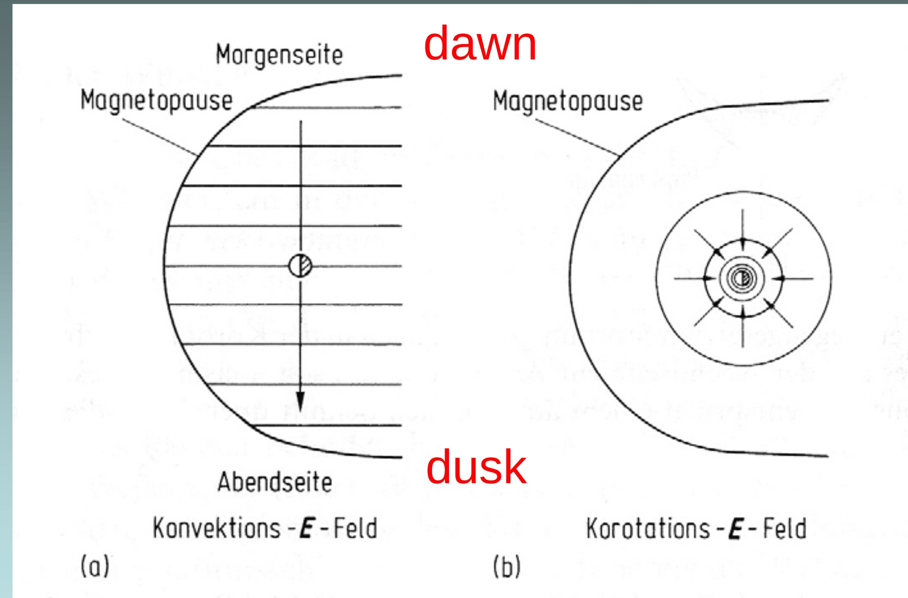
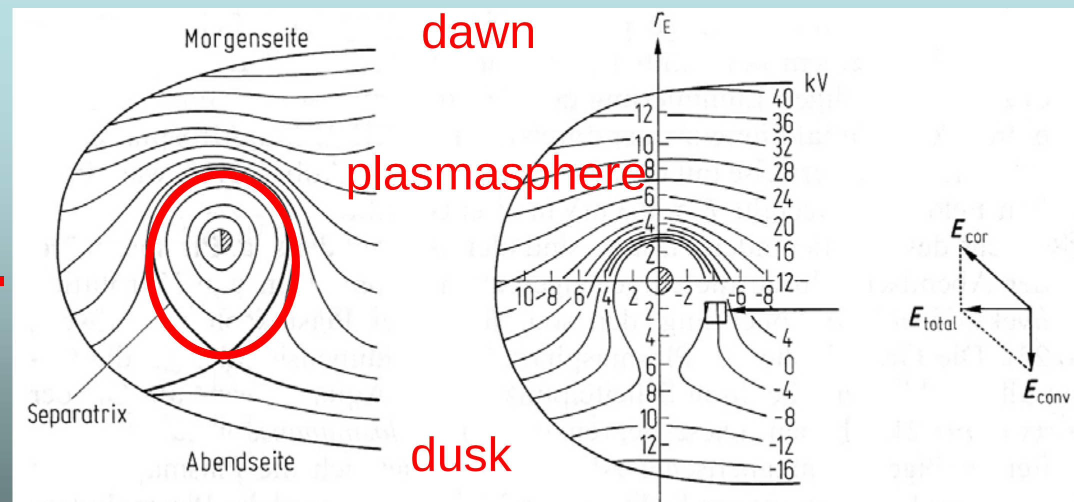
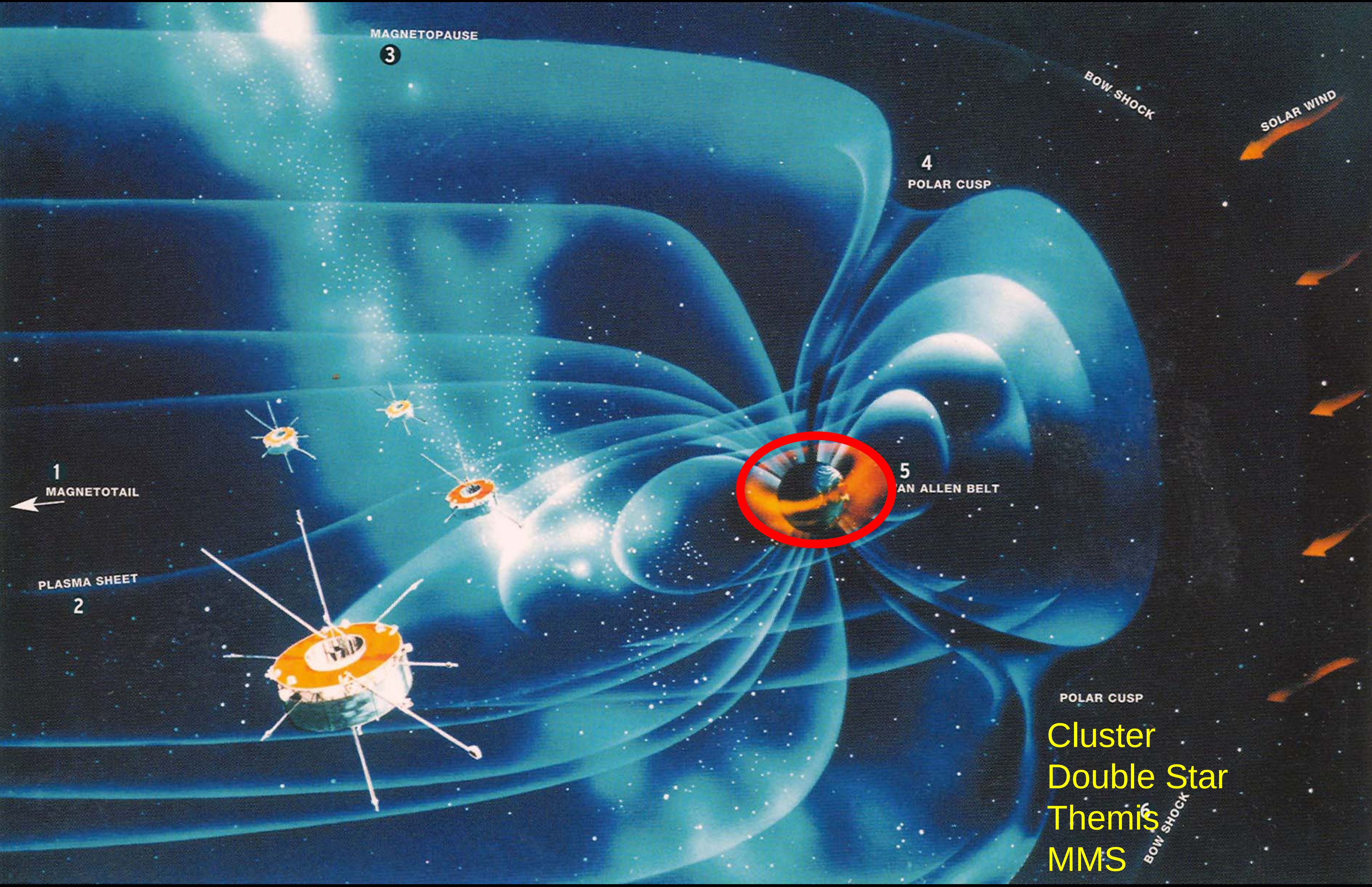
Inner-magnetospheric electric fields



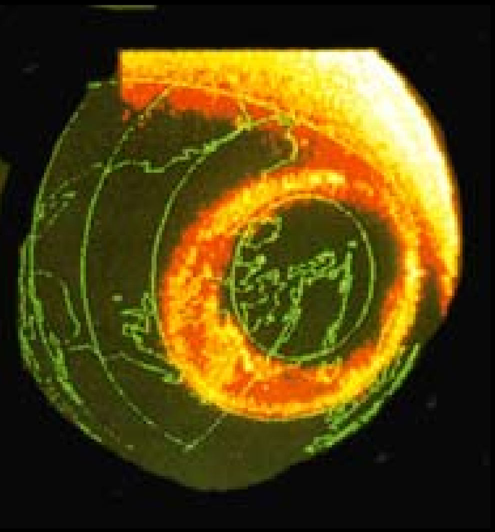
Inner-magnetospheric particle drift paths and iso-potential lines, resp.




MAGNETOPAUSE
3
BOW SHOCK
SOLAR WIND
4
POLAR CUSP
1
MAGNETOTAIL
5
AN ALLEN BELT
PLASMA SHEET
2
POLAR CUSP
BOW SHOCK
Cluster
Double Star
Themis
MMS

PLANETARY AURORAE

a fascinating phenomenon at and around the magnetic poles of magnetized planets



Earth
Dynamic Explorer)
UV - 130 nm
(Courtesy . L. Frank)

Jupiter
HST-STIS
UV - 150 nm
(R. Prangé & L Pallier)

Saturn
HST-STIS
UV - 130 nm
(R. Prangé & L Pallier)

PLANETARY AURORAE

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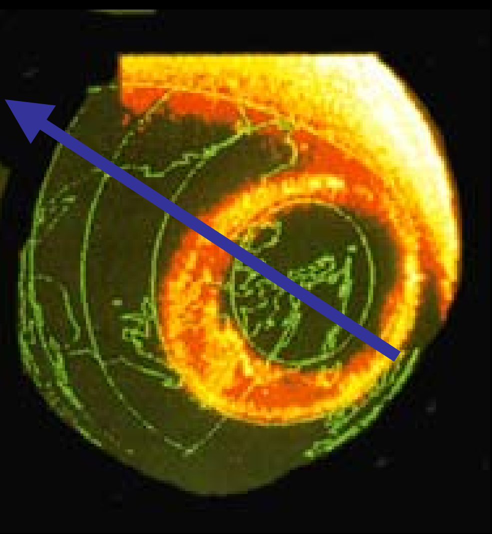

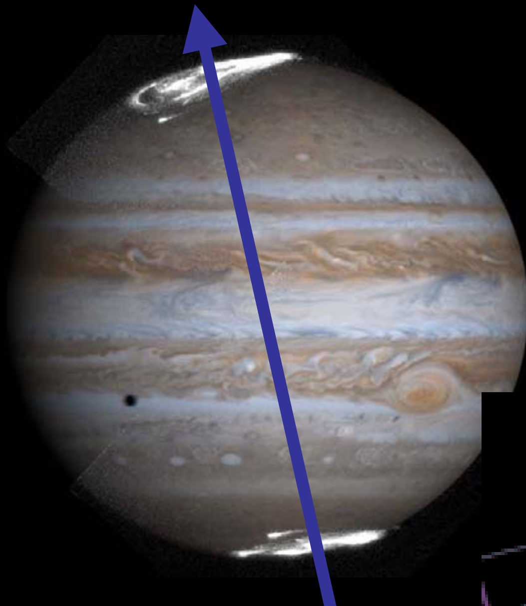

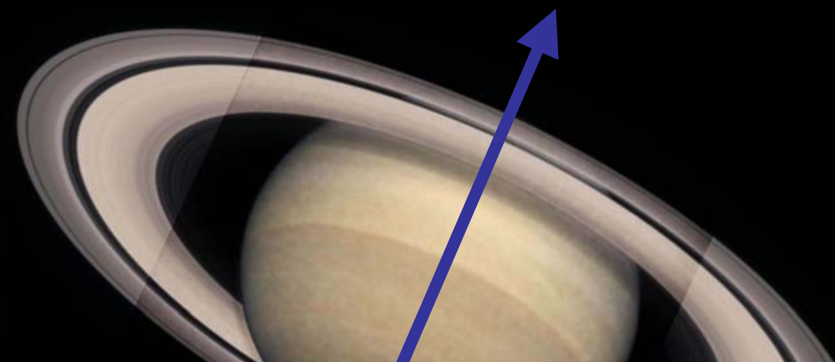

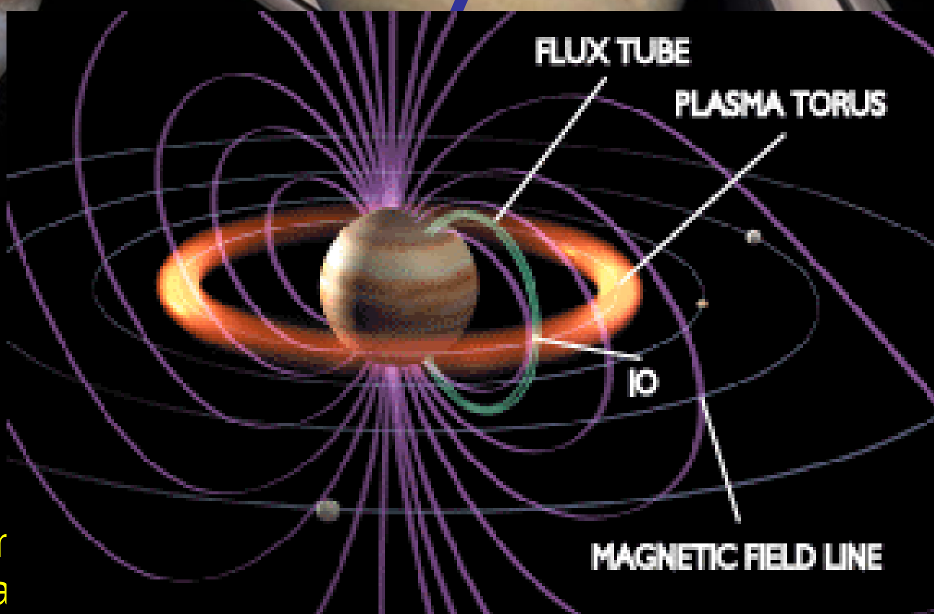

Earth
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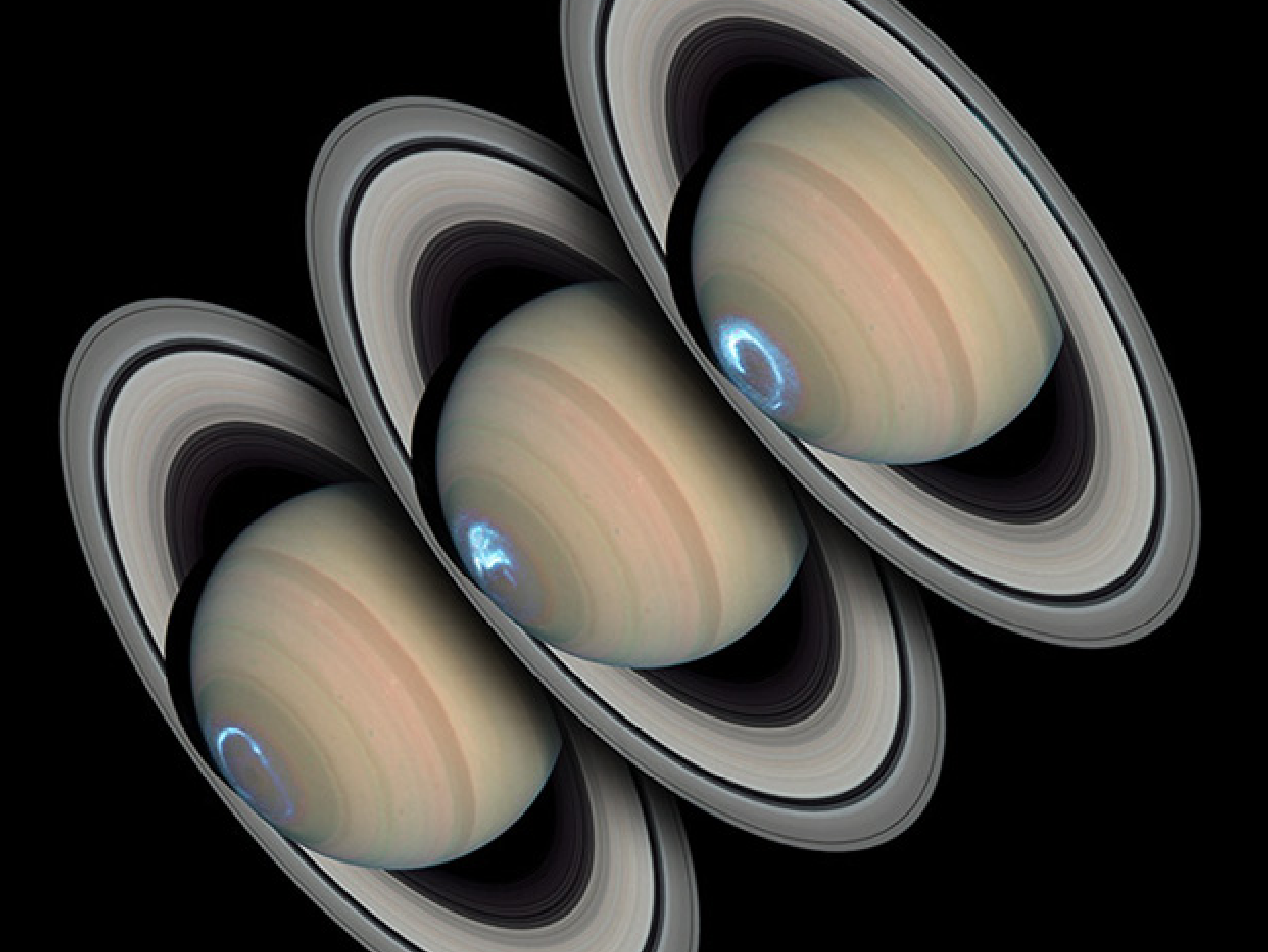
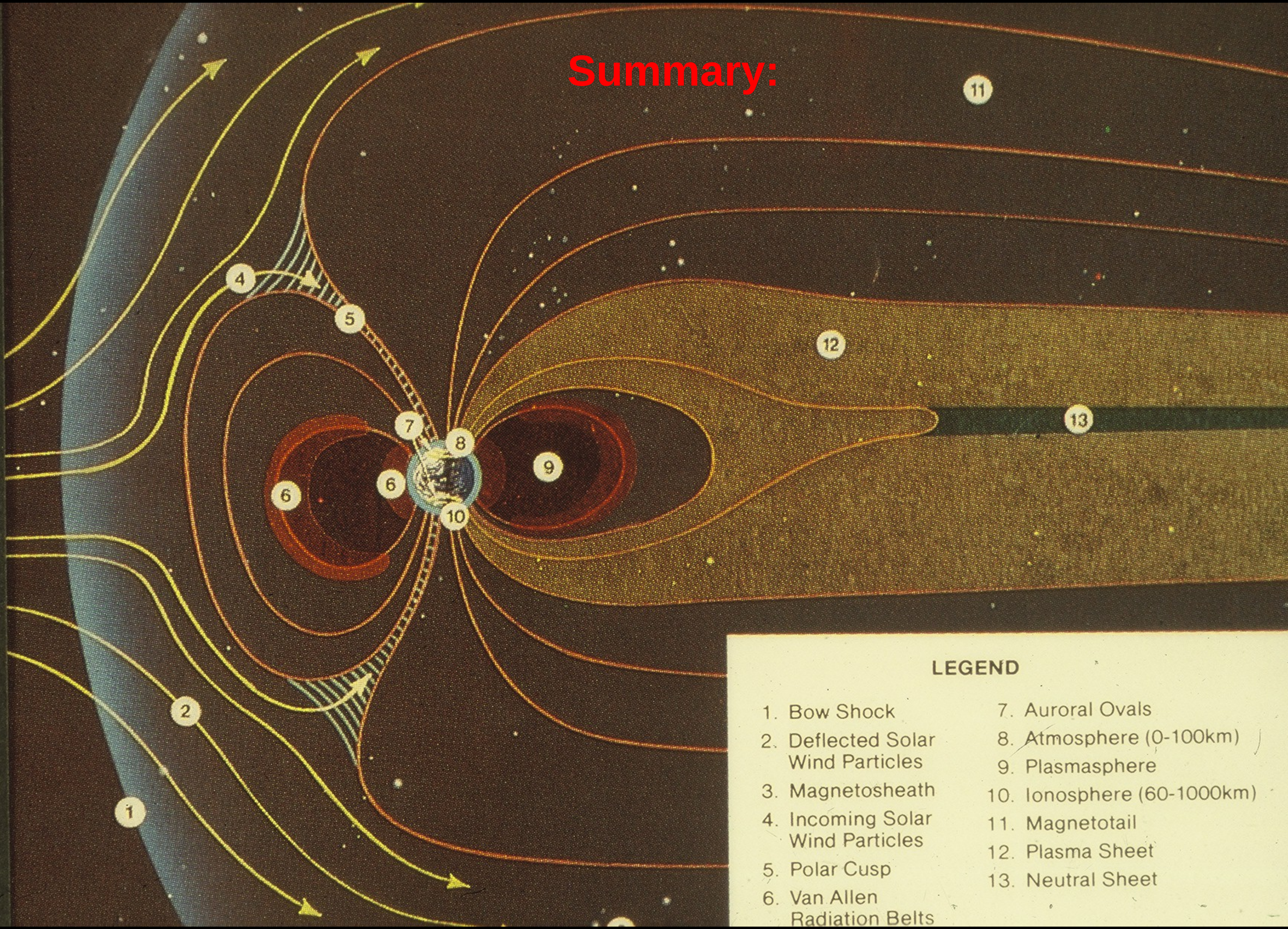


Summary:


LEGEND
1. Bow Shock
2. Deflected Solar Wind Particles
3. Magnetosheath
4. Incoming Solar Wind Particles
5. Polar Cusp
6. Van Allen Radiation Belts
7. Auroral Ovals
8. Atmosphere (0-100km)
9. Plasmasphere
10. Ionosphere (60-1000km)
11. Magnetotail
12. Plasma Sheet
13. Neutral Sheet

Magnetic field representation

$$B = -grad\Phi$$

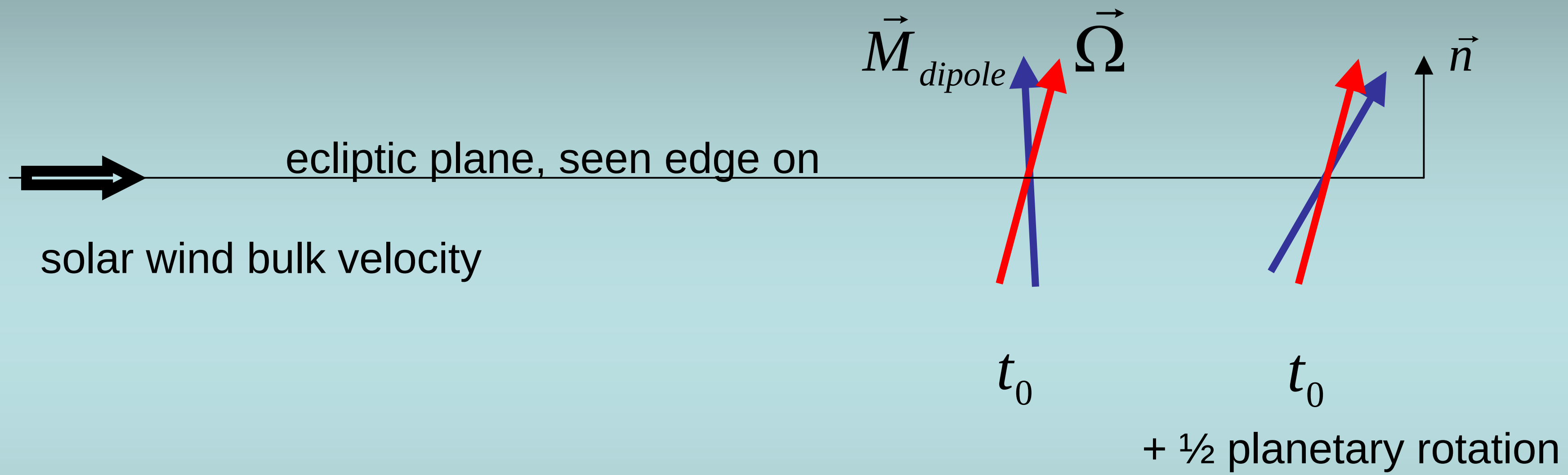
$$\Phi = r_p \sum_{n=1}^{\infty} (r_p / r)^{n+1} \left\{ \sum_{m=0}^{n} P_n^m(\cos\vartheta) \left[g_n^m \cos m\varphi + h_n^m \sin m\varphi \right] \right\}$$

Φ	magnetic potential
r_p	planetary radius
P_n^m	Legendre polynom
ϑ	polar distance angle
g_n^m, h_n^m	spherical harmonic coefficients
φ	planetocentric longitude

Magnetic properties of the magnetized planets

Planet (Radius in km)	Erde (6378)	Jupiter (71372)	Saturn (60330)	Uranus (25600)	Neptun (24765)
Modell	IGRF 85[a]	O4	Z3	Q3	O8
g(1,0)	−0.29877	+4.2180	+0.21535	+0.11893	+0.09732
g(1,1)	−0.01903	−0.6640	0	+0.11579	+0.03220
h(1,1)	+0.05497	+0.264	0	−0.15685	−0.09889
g(2,0)	−0.02073	−0.203	+0.01642	−0.06030	+0.07448
g(2,1)	+0.03045	−0.735	0	−0.12587	+0.00664
h(2,1)	−0.02191	−0.469	0	+0.06116	+0.11230
g(2,2)	+0.01691	+0.513	0	+0.00196	+0.04499
h(2,2)	−0.00309	+0.088	0	+0.04759	−0.00070
g(3,0)	+0.01300	−0.233	+0.02743	0	−0.06592
g(3,1)	−0.02208	−0.076	0	0	+0.04098
h(3,1)	−0.00312	−0.580	0	0	−0.03669
g(3,2)	+0.01244	+0.168	0	0	−0.03581
h(3,2)	+0.00284	+0.487	0	0	+0.01791
g(3,3)	+0.00835	−0.231	0	0	+0.00484
h(3,3)	−0.00296	−0.294	0	0	−0.00770
Dipolmoment	$0.304\ 10^{-4}\ \mathrm{T}R_E^3$	$4.28\ 10^{-4}\ \mathrm{T}R_J^3$	$0.215\ 10^{-4}\ \mathrm{T}R_S^3$	$0.228\ 10^{-4}\ \mathrm{T}R_U^3$	$0.142\ 10^{-4}\ \mathrm{T}R_N^3$
Dipolneigung	+11.4°	−9.6°	−0.0°	−58.6°	−46.9°
OTD[b]	$0.08\ R_E$	$0.07\ R_J$	$0.04\ R_S$	$0.31\ R_U$	$0.55\ R_N$
Äquatorneigung	23.45°	3.1°	26.7°	97.8°	28.8°

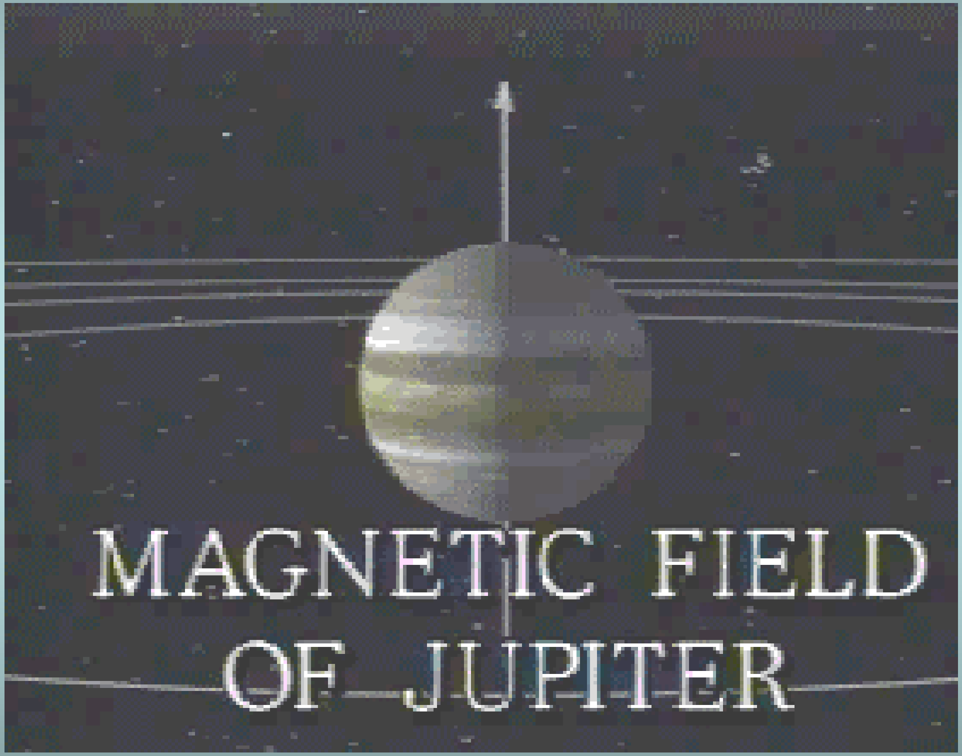
Classification of magnetospheric structures



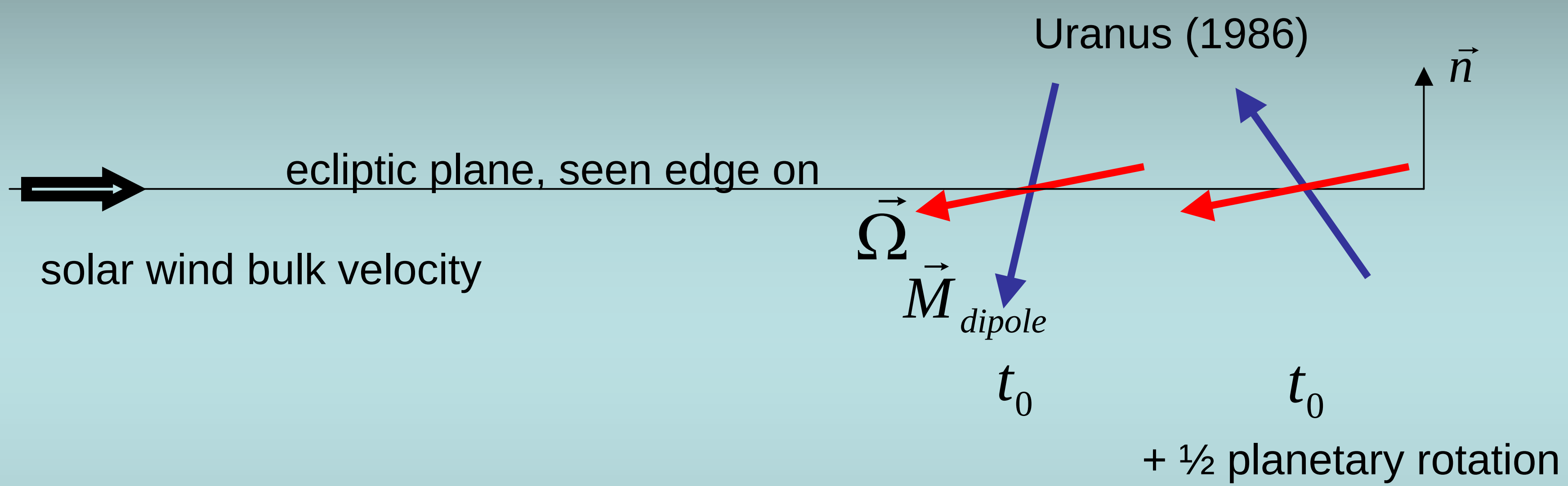
	$\vec{\Omega}, \vec{n}$	$\vec{\Omega}, \vec{M}$
Earth	23.45°	11.4°
Jupiter	3.1°	9.6°
Saturn	26.7°	+/- 0°

„symmetrical" magnetospheres

Magnetic field of Jupiter



Classification of magnetospheric structures



	$\vec{\Omega}, \vec{n}$	$\vec{\Omega}, \vec{M}$
Uranus	97.8°	58.6°
Neptune	28.3°	46.9°

„oblique rotators“

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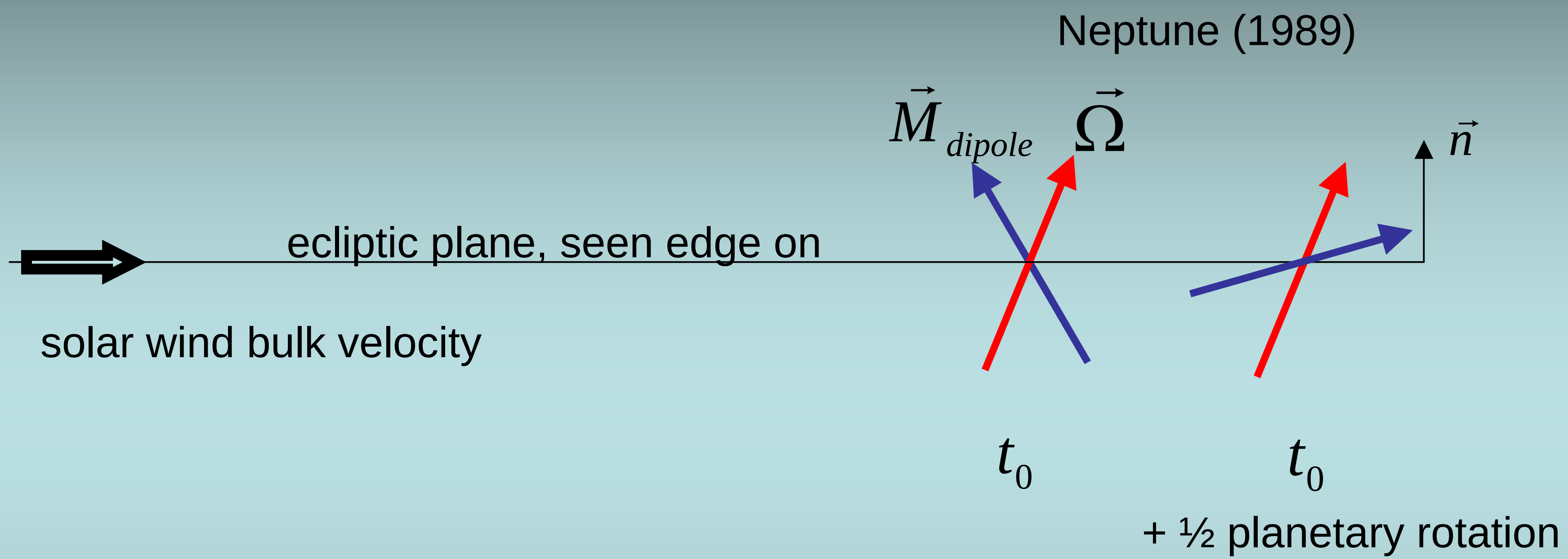

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„Advertisement“ for tomorrow:

Space missions to the outer planets

Saturn, as seen by Cassini