Astrophysical / Solar system Plasmas : an introduction

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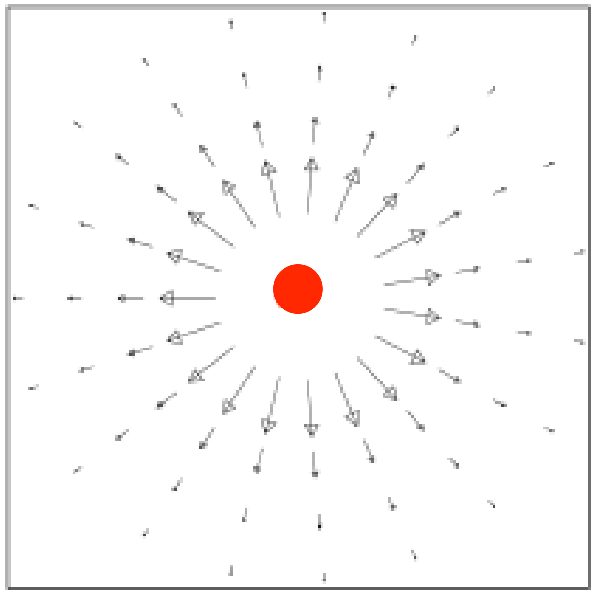
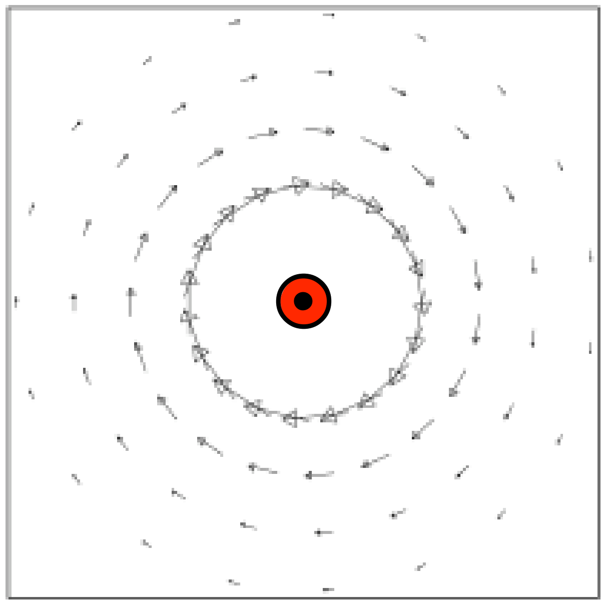
- Plasma = 4^{th} state of matter

- electrons + ions → E & B (via J)



- Coulomb + Lorentz forces : $F = qE + qv \times B$



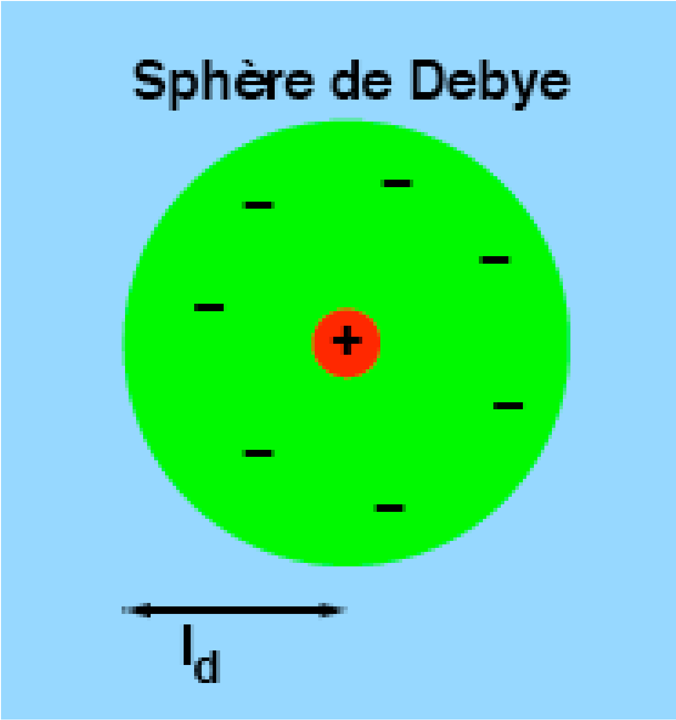
- Long range interactions (E in q/r^2)

- Fields/particles/currents related via Maxwell equations

$$\nabla \cdot B = 0$$
$$\nabla \cdot E = \rho/\epsilon_o$$
$$\nabla \times E = -\partial B/\partial t$$
$$\nabla \times B = \mu_o J \; (+ \; 1/c^2 \; \partial E/\partial t)$$

- Debye screening : potential V in e^{-r/L_d} beyond the Debye length L_d

  (where $eV \sim kT$ ➔ $L_d = (\epsilon_0 kT/Ne^2)^{1/2}$ decreases with N, increases with T)

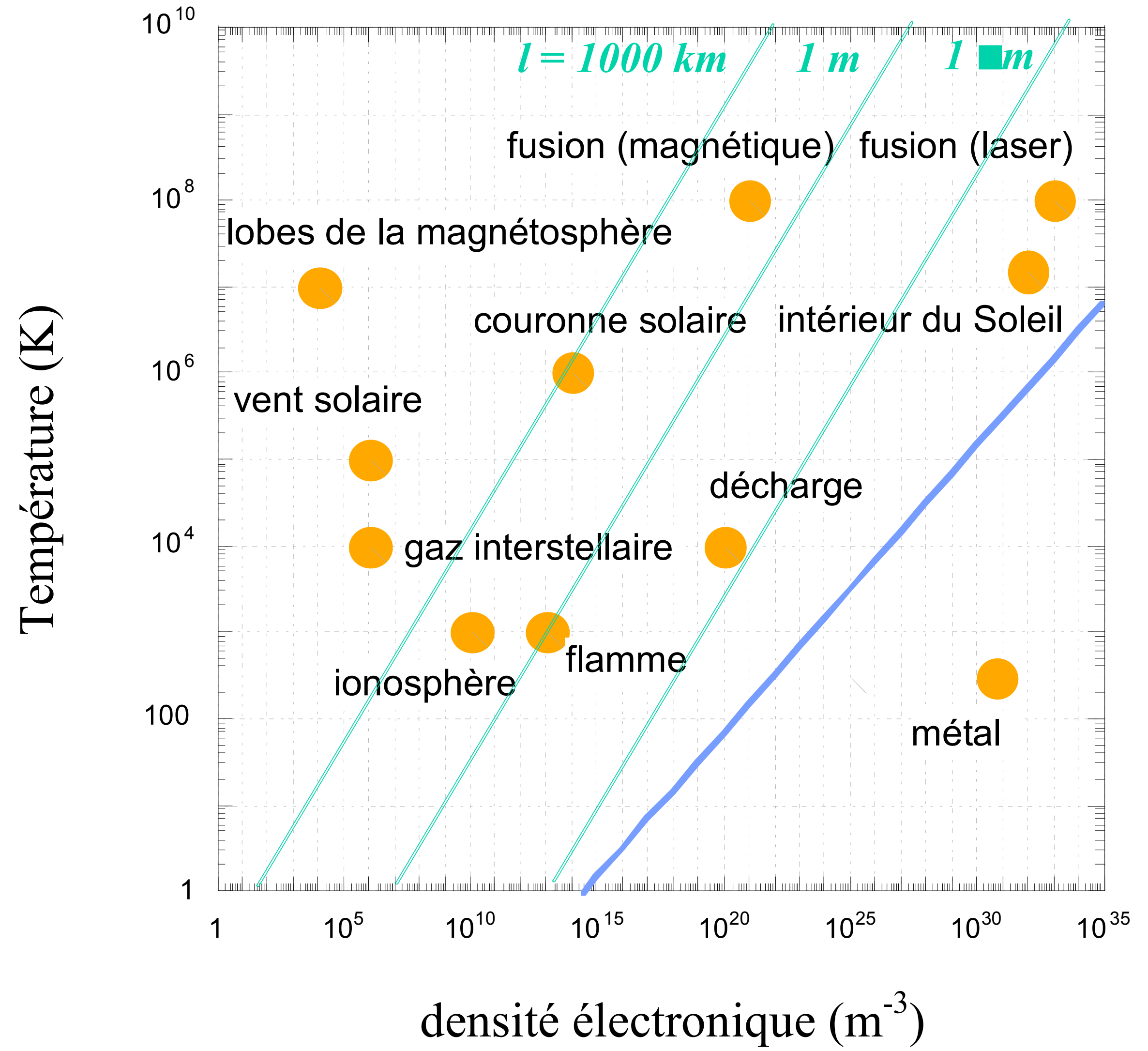


- Quasi-neutrality at scales $L > L_d$ ➔ no large scale E field at equilibrium
- $N_i \sim N_e$ (within 10^{-6}, fluctuations of order $\delta V \sim kT/e$ still possible)

- <u>Plasma</u> ➔ requires

  - many particles in Debye sphere,
  - $L_d \ll L_{system}$
  - not too many collisions

    ($f_{coll\text{-}e\text{-}i}$ in $NT^{-3/2}$, mean free path in T^2/N)



- Collective effects appear due to long range interactions :

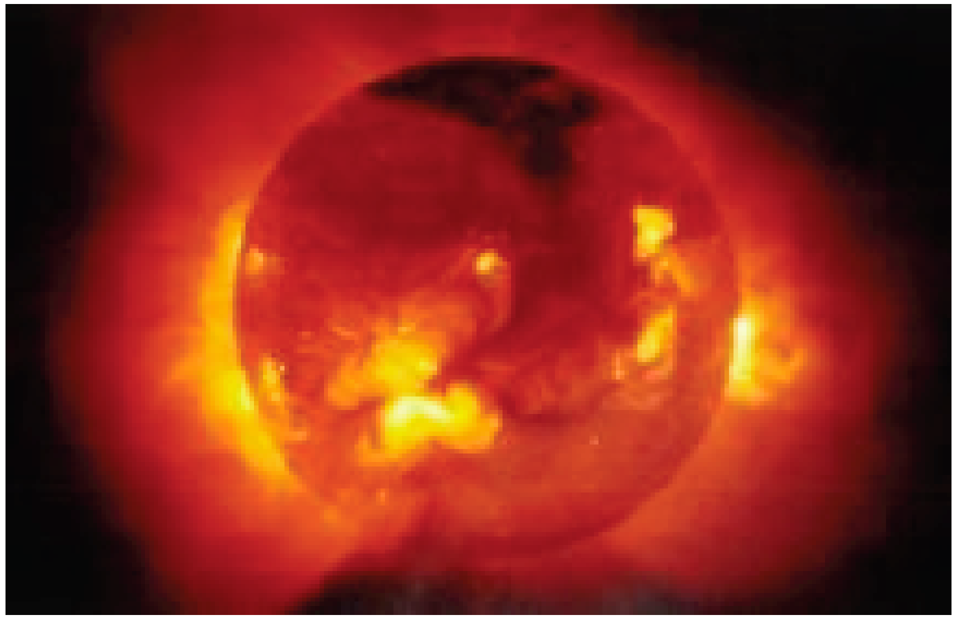
  - Natural (relaxation) oscillation at $f_{pe,i} = (1/2\pi)\,(Ne^2/\epsilon_o m_{e,i})^{1/2}$
  - Cyclotron motion at $f_{ce,i} = eB/2\pi m_{e,i}$

    (with Larmor radius $r_L = m_{e,i} V_{\perp} / eB$)

  ...

➔ waves

	Solar corona	Interplanetary medium	Terrestrial ionosphere
T (K)	10^6	4×10^5	~300
N (cm^{-3})	10^4	10	4×10^5
B (G)	10^{-2}	10^{-5}	10^{-1}
L_d (m)	0.7	14	0.002
N_d	1.4×10^{10}	10^{11}	10^4
e^- mean free path (m)	3×10^{11}	5×10^{13}	~700
r_{Li} (m)	1300	10^6	2
L_{system} (m)	$\sim7\times10^8$	$\sim10^{8-11}$	$\sim10^{5-6}$
f_{pe} (Hz)	9×10^5	3×10^4	6×10^6
f_{pi} (Hz)	2×10^4	700	10^5
f_{ce} (Hz)	3×10^4	30	3×10^5
f_{ci} (Hz)	1400	10^{-2}	14000
$f_{coll-e-i}$ (Hz)	3×10^{-5}	10^{-7}	230
τ_{diff} (s)	6×10^{18} (10^{11} years)	$3\times10^{16-22}$ (10^{9-15} years)	$6\times10^{5-7}$



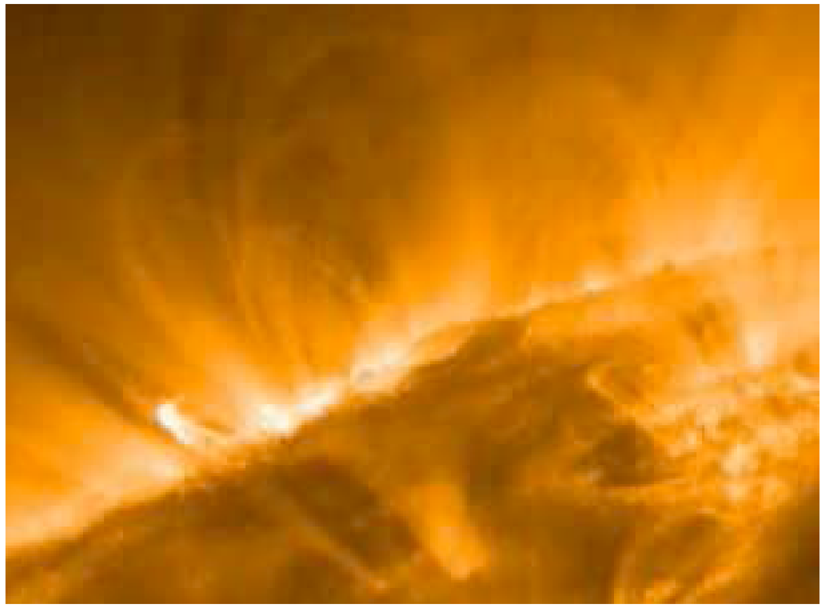
X-ray Sun

Tarantula nebula

Universe = 99% plasma !

Solar wind and magnetospheres

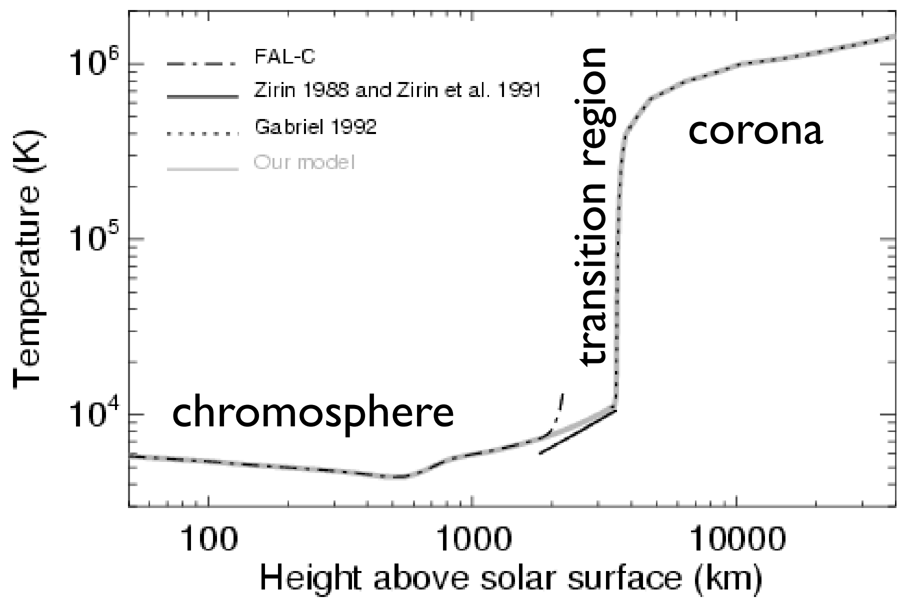
Céline Boutry "Turbulence in the solar corona"



Solar corona : $T=1\text{-}2\times10^6$ K (cf. Fe XXV+ lines...),

while photosphere at 6000K (chromosphere ~20000 K)

- Photosphere : $1\ R_S$ $T = 6000$ K $N \geq 10^{14}\ cm^{-3}$
  $B \sim 1$ G (up to 10^3 in spots)
- Low Corona : $2\ R_S$ $T \sim 10^6$ K $N = 10^{5-6}\ cm^{-3}$
  $B \sim 1$ G
- High Corona : $10\ R_S$ $T \sim 10^6$ K $N = 10^{3-4}\ cm^{-3}$
  $B \sim 10^{-2}$ G

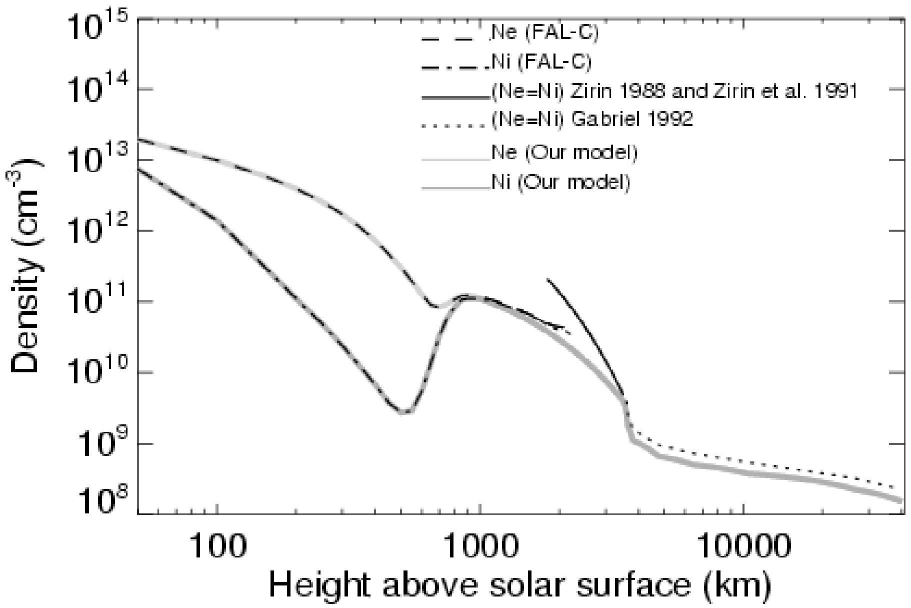


Energy flux $\propto N T v_{sound} \propto N T^{3/2}$

→ $(NT^{3/2})_{corona}/(NT^{3/2})_{photosphere} \ll 1$

Enough energy present but heating mechanism ?

→ Turbulence ?



- Solar corona hot ➔ out of hydrostatic equilibrium

  ➔ permanent escape, accelerated to 400-800 km/s (how exactly ?)

  = Solar Wind

B(t) obeys to $\nabla\times E = -\partial B/\partial t$ $\nabla\times B = \mu_o J$ $J = \sigma E$ ($\sigma = 10^{-2} T^{3/2}$ ohm^{-1}m^{-1})

➔ $\nabla^2 B = \sigma\, \mu_o\, \partial B/\partial t$ (B field diffusion through the medium)

➔ $\delta B/\delta t \sim (\sigma\, \mu_o)^{-1}\, \delta B/(\delta s)^2$

➔ $\tau_{diff} \sim \sigma\, \mu_o\, L_{system}^2$

B & plasma « frozen » together

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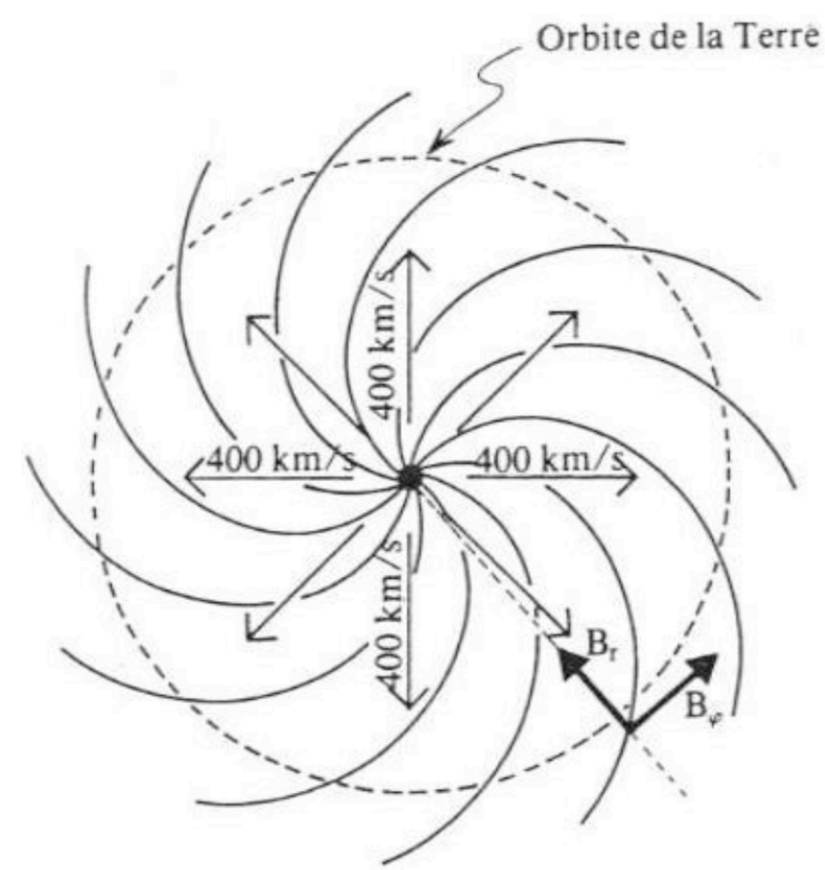
Plasma $\beta = NkT/(B^2/2\mu_o) \sim 1$, but $(NmV^2/2)/(B^2/2\mu_o) \sim 10$

→ solar magnetic field convected with the solar wind

→ Parker spiral



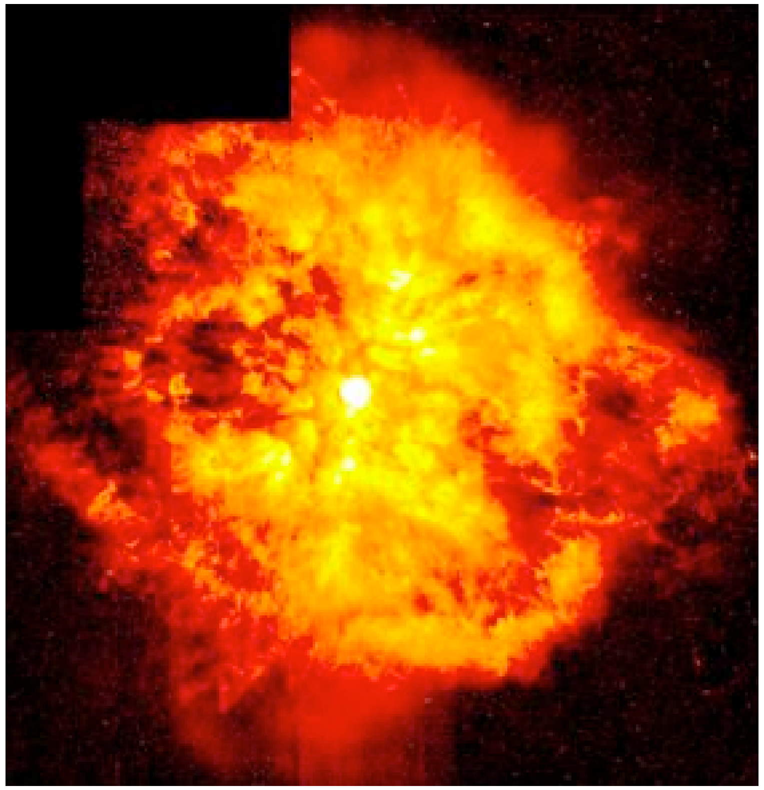
Gaétan le Chat "Study of stellar wind energy flux: from the Sun to Betelgeuse"

Comparison of solar wind energy flux (kinetic + potential, due to mass loss), from Wind and Ulysses spacecraft observations (in & out ecliptic)

➔ dependence on heliocentric latitude and wind speed (found ~constant)

➔ comparison to stellar wind energy fluxes (several classes identified)

➔ winds origins (main sequence, cool giants
+ specific power source for T-Tauri ?)



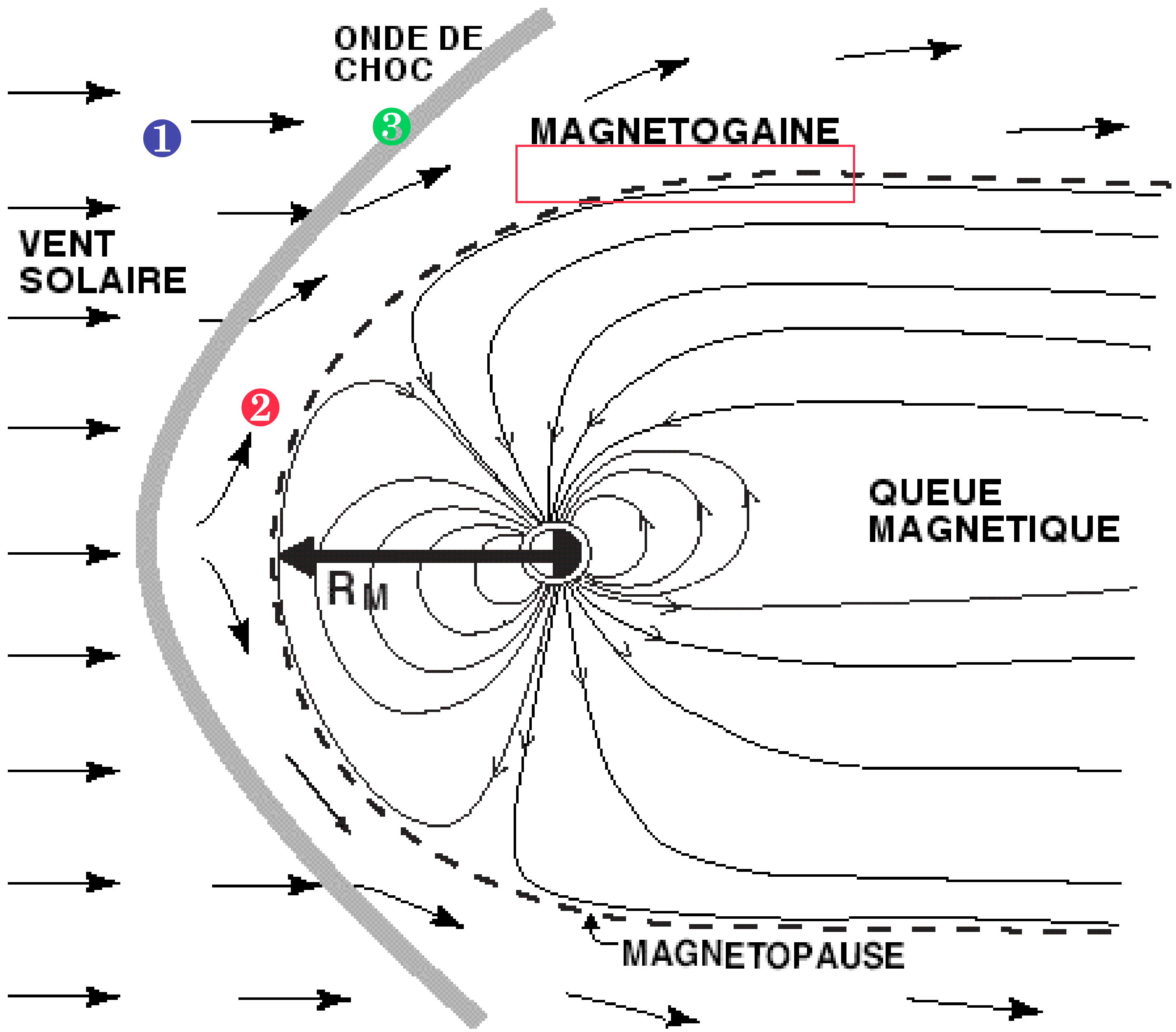
M1-67 nebula: a massive stellar wind

- When solar wind meets a planetary obstacle formation of a magnetosphere bounded by a magnetopause + shock but collisionless !

  ❶ « upstream » unperturbed flow

  ❷ near obstacle : P, ρ, T ↑ fast, i.e. ~adiabatically : $P \propto \rho^{\gamma} \rightarrow V_s \;\alpha\; (P/\rho)^{1/2} \;\alpha\; \rho^{(\gamma-1)/2} \uparrow$
  mass flux conservation → V↓ → the flow becomes subsonic

  ❸ thin transition ~ $r_{Li} \leq 10^3$ km ~ discontinuity = « bow shock »



→ energy and momentum must be redistributed via waves …

Joël Stienlet "Simulation PIC 2D of a collisionless shock wave"

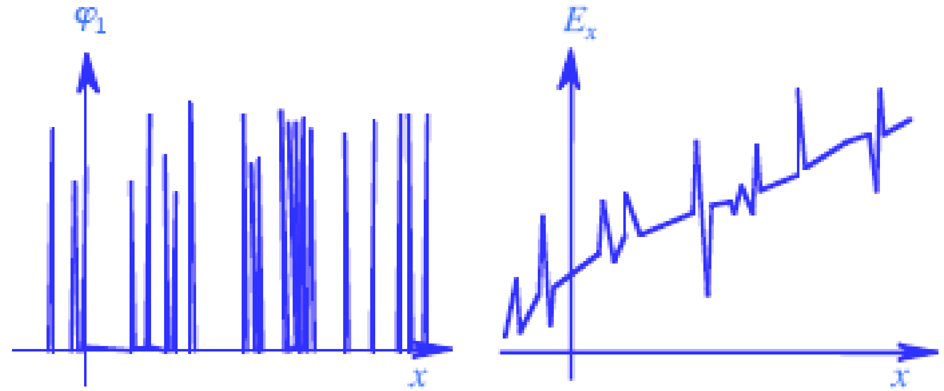
- Plasma physics simulation codes (by decreasing « complexity ») :
  - N-body → x_i, v_i, E, B
  - Kinetic → f(x,v), E, B → with collisions : Boltzmann, Fokker-Planck equations
    → without collision : Vlasov equation
  - MHD assumes ETL (f(x,v) Maxwellian) → fluid description of plasma using moments (N,V,T...) of f(x,v)

- Choice of code depends on scales (t,x) of phenomena studied

- PIC = N-body for particles + fields computed on a grid at each time step (Maxwell-Poisson/Vlasov)

<u>N-body</u>

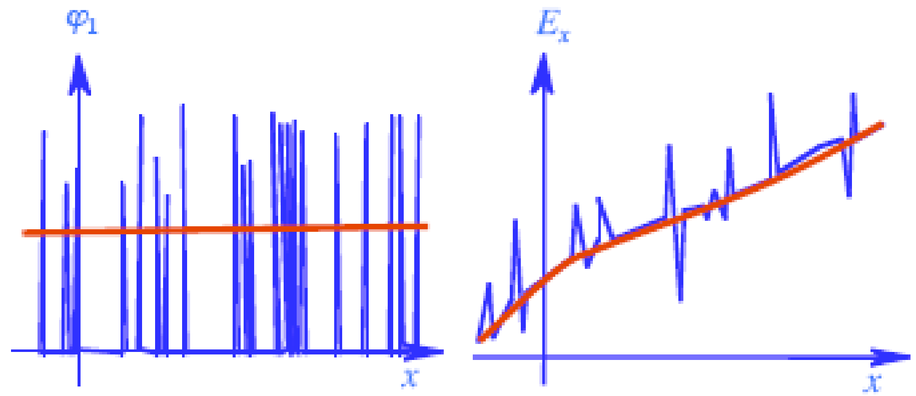
$$\varphi(\mathbf{r},\mathbf{w},t)=\sum_i \delta(\mathbf{r}-\mathbf{r}_i(t))\delta(\mathbf{w}-\mathbf{w}_i(t))$$



$$\begin{cases} \dot{\mathbf{x}}_i = \mathbf{w}_i \\ \dot{\mathbf{w}}_i = \mathbf{F}(\mathbf{x}_i,\mathbf{w}_i)/m \end{cases}$$

<u>Kinetic</u>

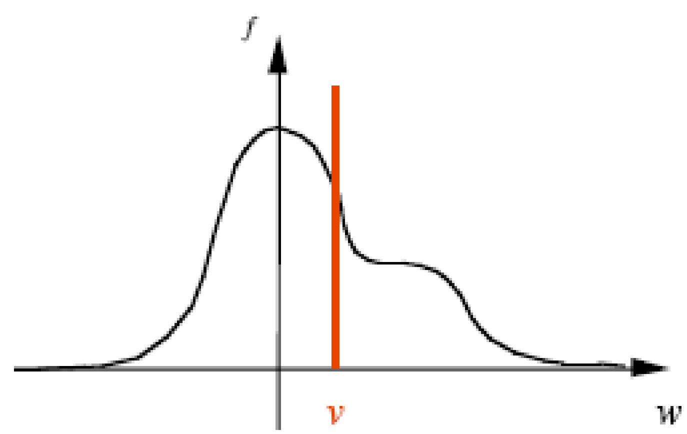
$$f(\mathbf{r},\mathbf{w},t)=\frac{1}{\delta V}\int_{\delta V} \varphi_1(\mathbf{r}',\mathbf{w}',t)d^3\mathbf{r}'d^3\mathbf{w}'$$



$$\partial_t(f)+\mathbf{w}.\nabla_x(f)+\left\langle\frac{\mathbf{F}}{m}\right\rangle.\nabla_w(f)=-C_1$$

<u>MHD</u>

$$n=\int f(\mathbf{w})d^3\mathbf{w}$$
$$nm\mathbf{v}=\int m\mathbf{w}f(\mathbf{w})d^3\mathbf{w}=nm<\mathbf{w}>$$
...

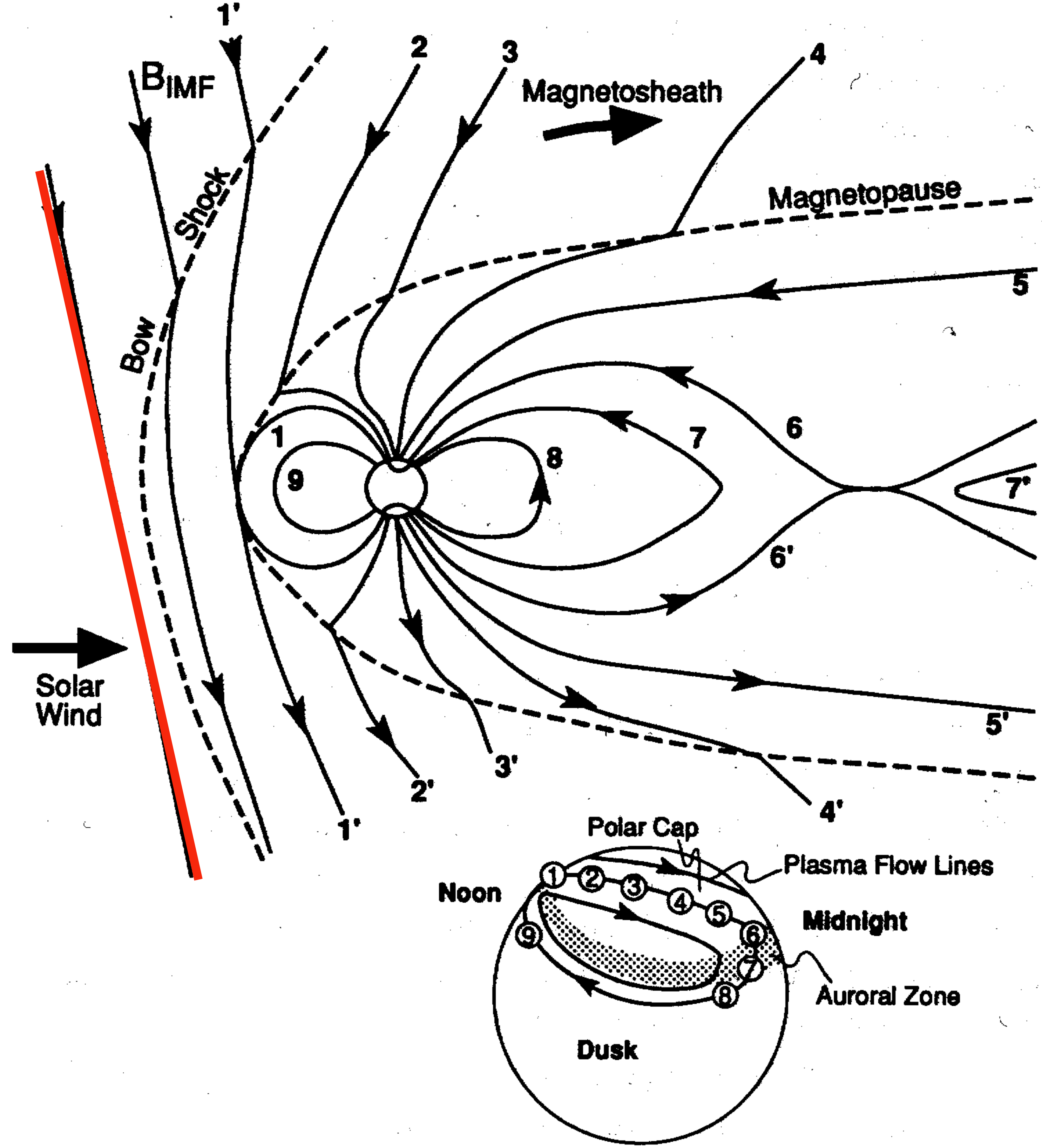


$$\partial_t(n)+\nabla.(n\mathbf{v})=0$$
$$\partial_t(nm\mathbf{v})+\nabla.(nm\mathbf{v}\mathbf{v}+\overline{\overline{\mathbf{p}}})=nq(\mathbf{E}+\mathbf{v}\times\mathbf{B})$$
....

Nicolas Aunai "Asymmetric magnetic reconnection"

Magnetopause not totally impermeable ➔ mass and energy entry in Magnetosphere via magnetic field line « reconnection » [possibly also via polar cusps]

Then transport day ➔ night, followed by 2nd reconnection in magnetospheric tail



B IMF
1'
2
3
4
Magnetosheath
Bow Shock
Magnetopause
5
1
9
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6
7'
6'
Solar Wind
5'
1'
2'
3'
4'
Polar Cap
Plasma Flow Lines
Noon
Midnight
Auroral Zone
Dusk
1
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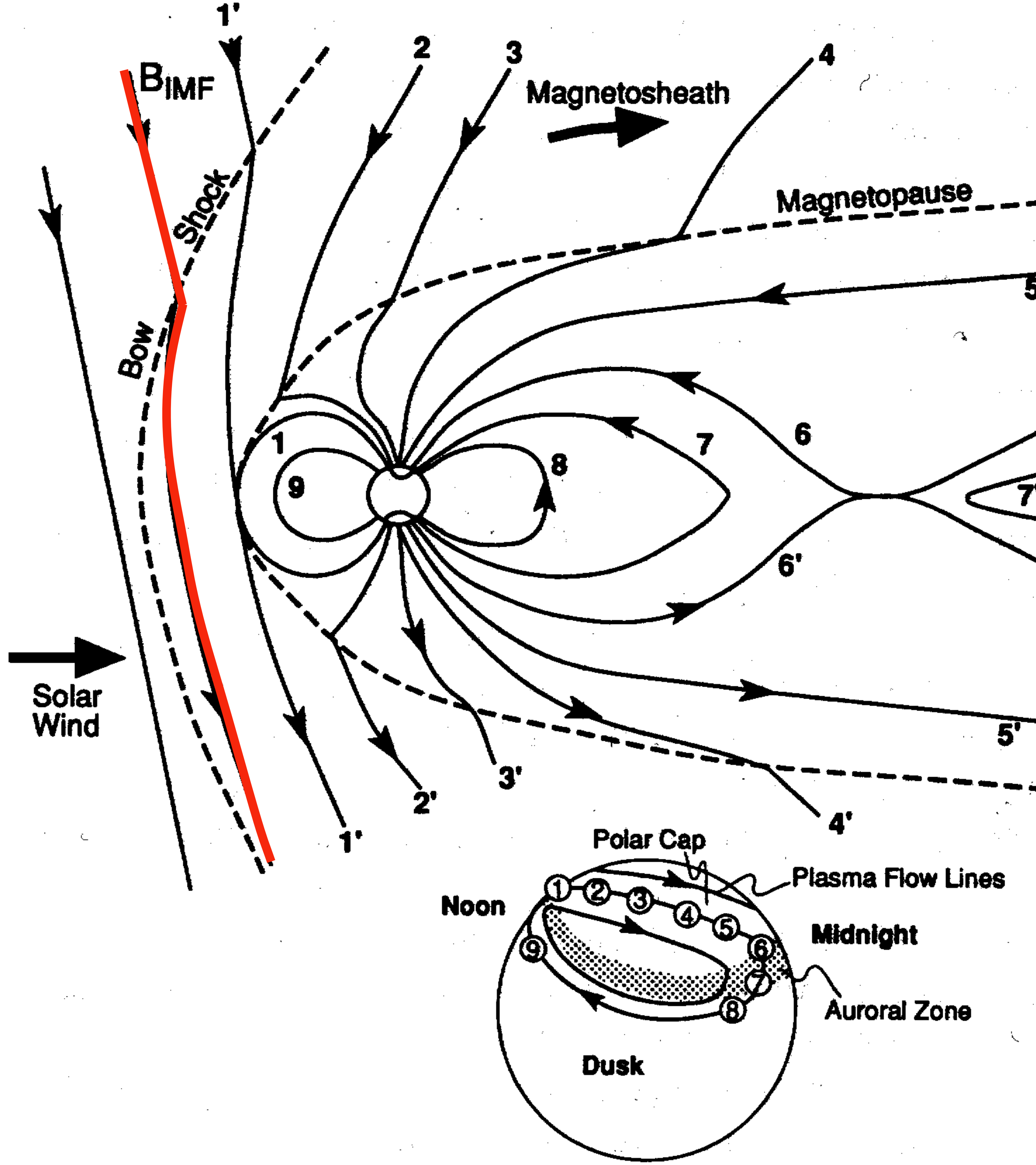
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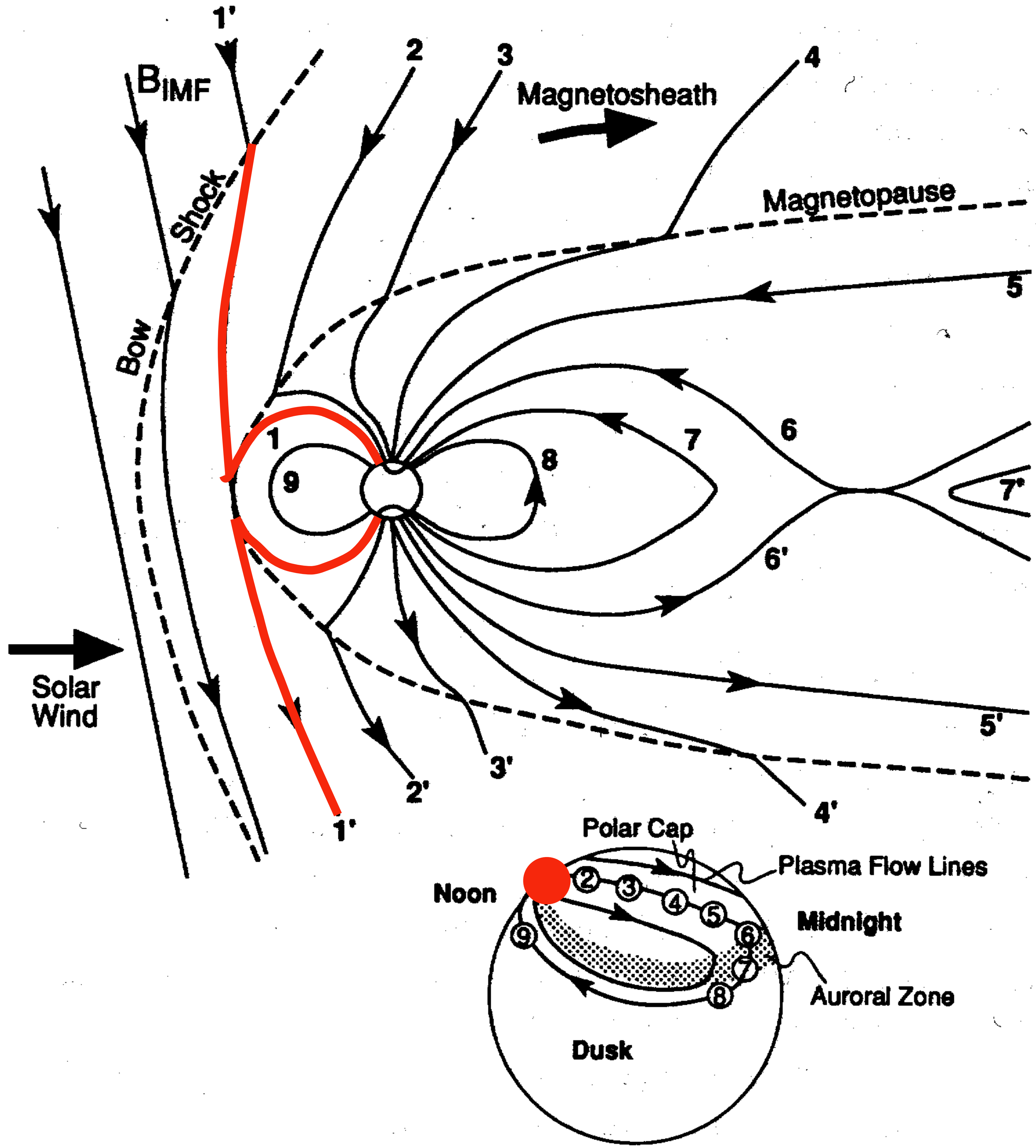
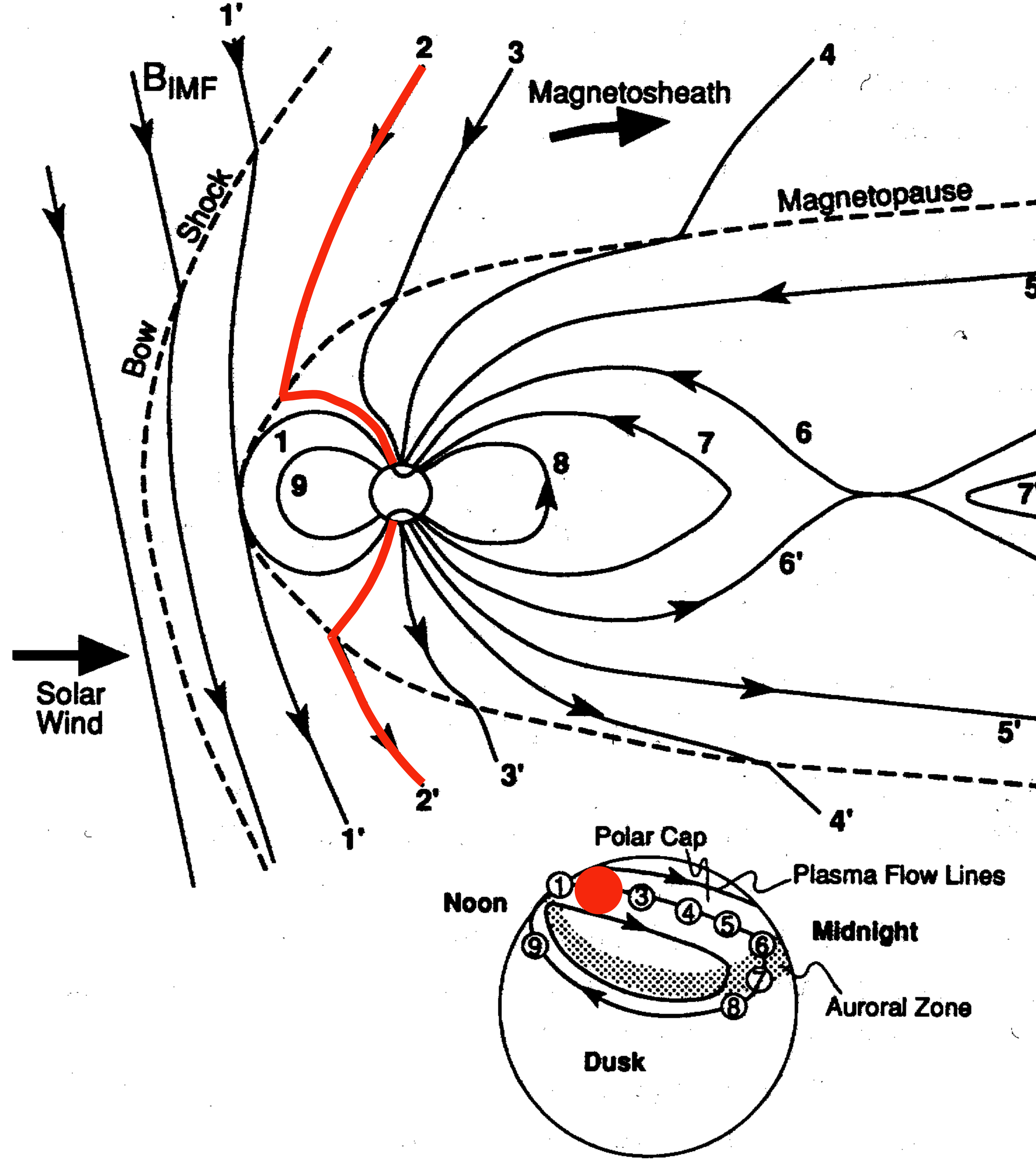
1'
Polar Cap
Plasma Flow Lines
Noon
Midnight
Auroral Zone
Dusk

1_{st} reconnection (magnetopause) = start cycle





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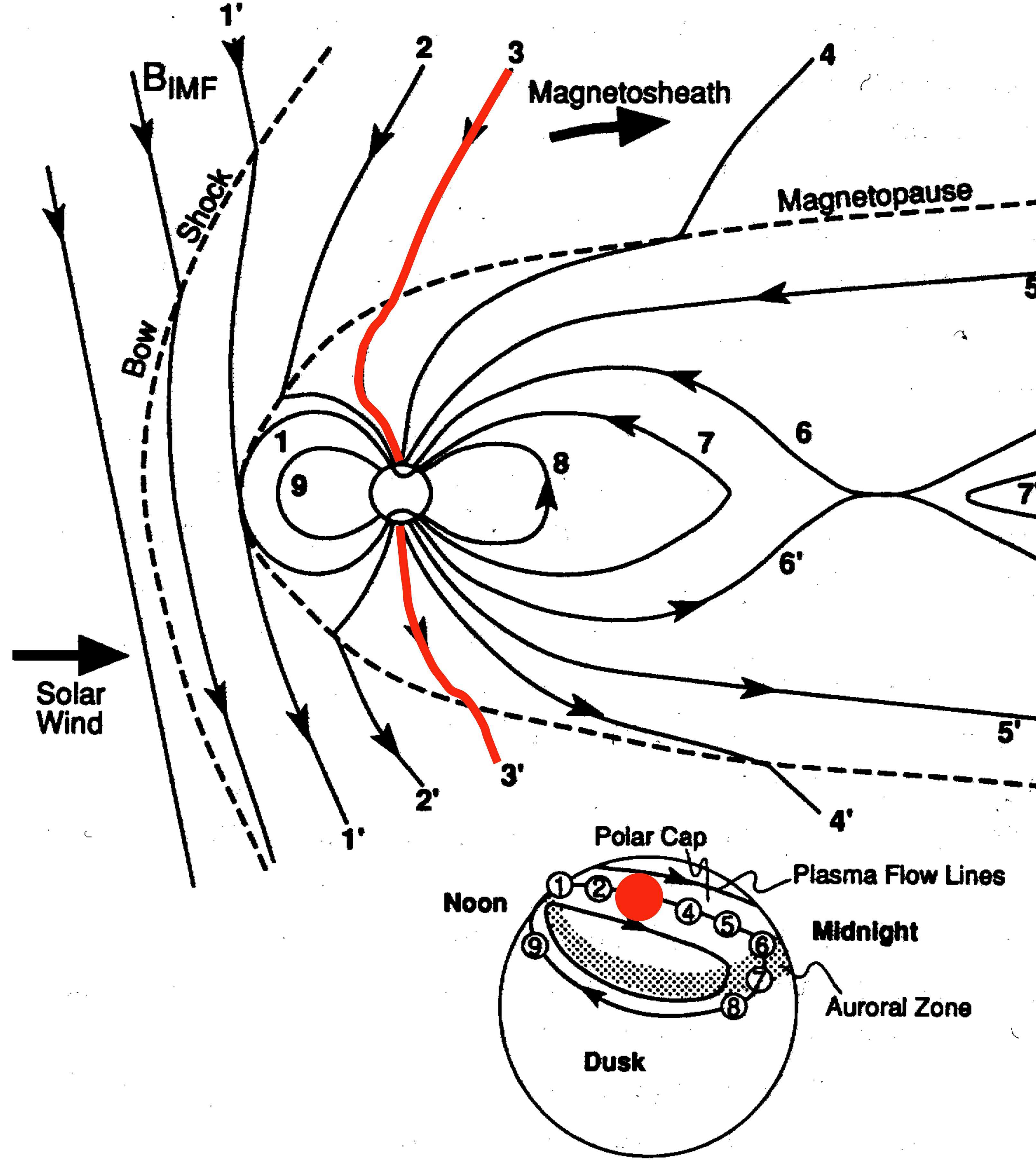
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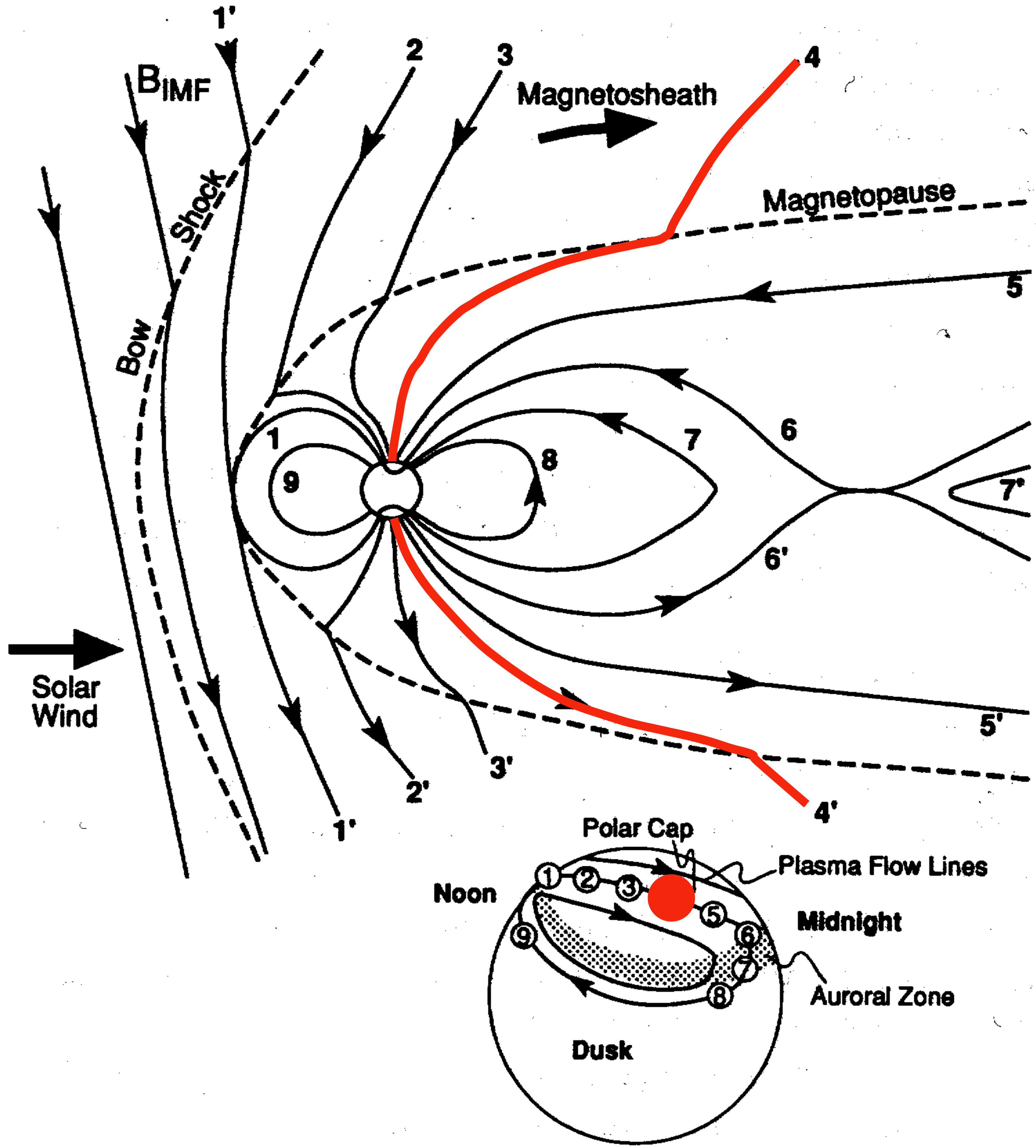
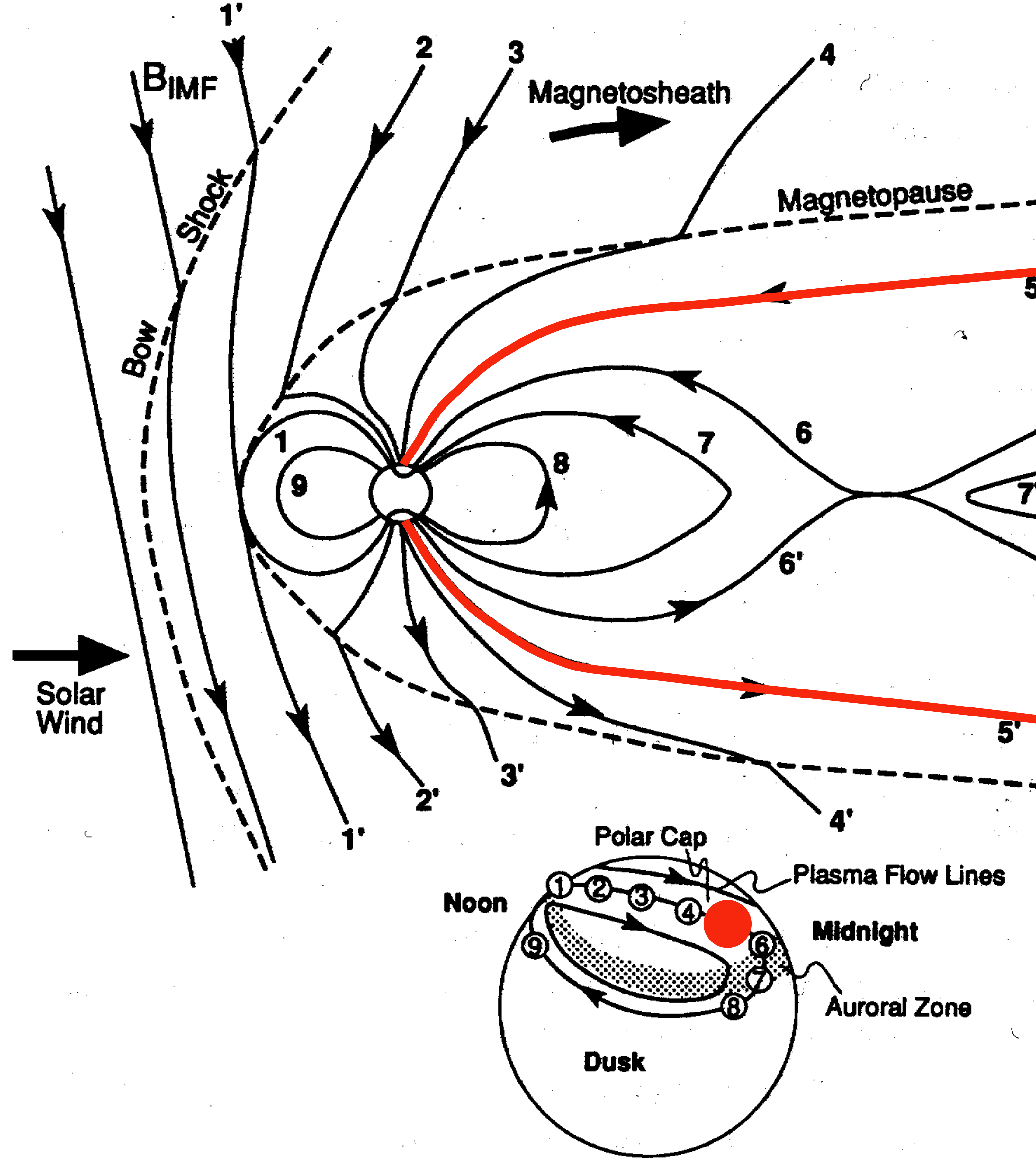
transport
above
poles

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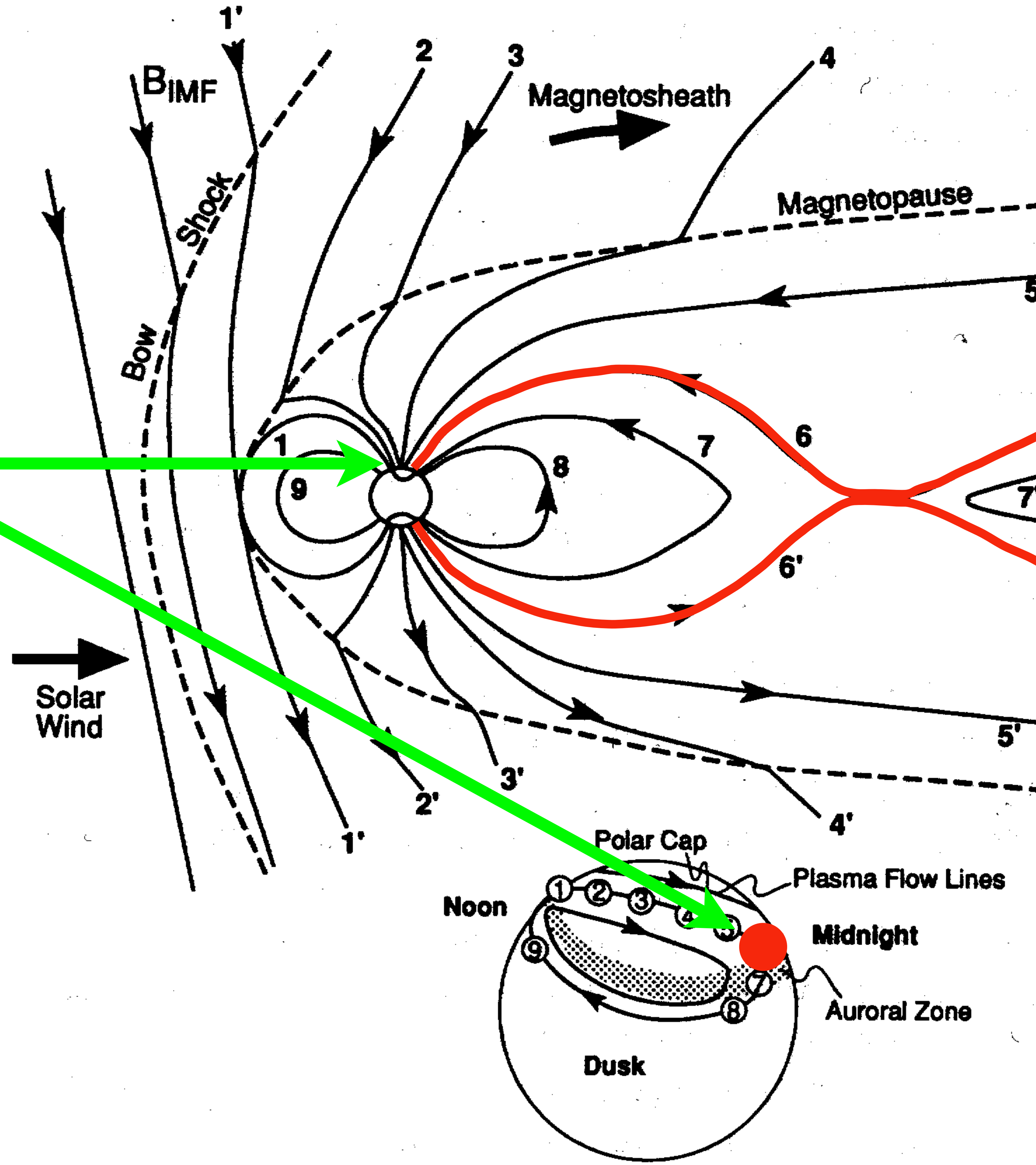
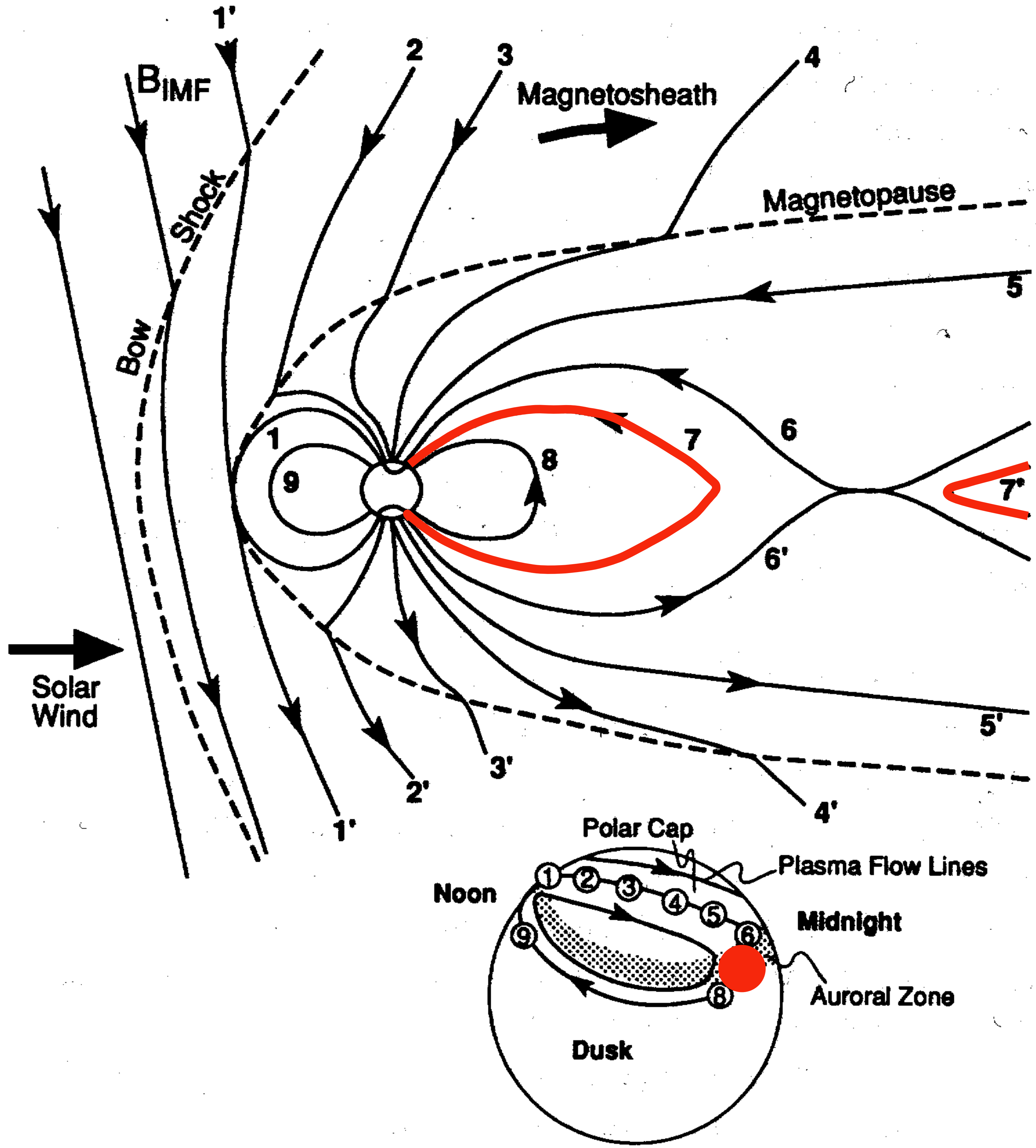
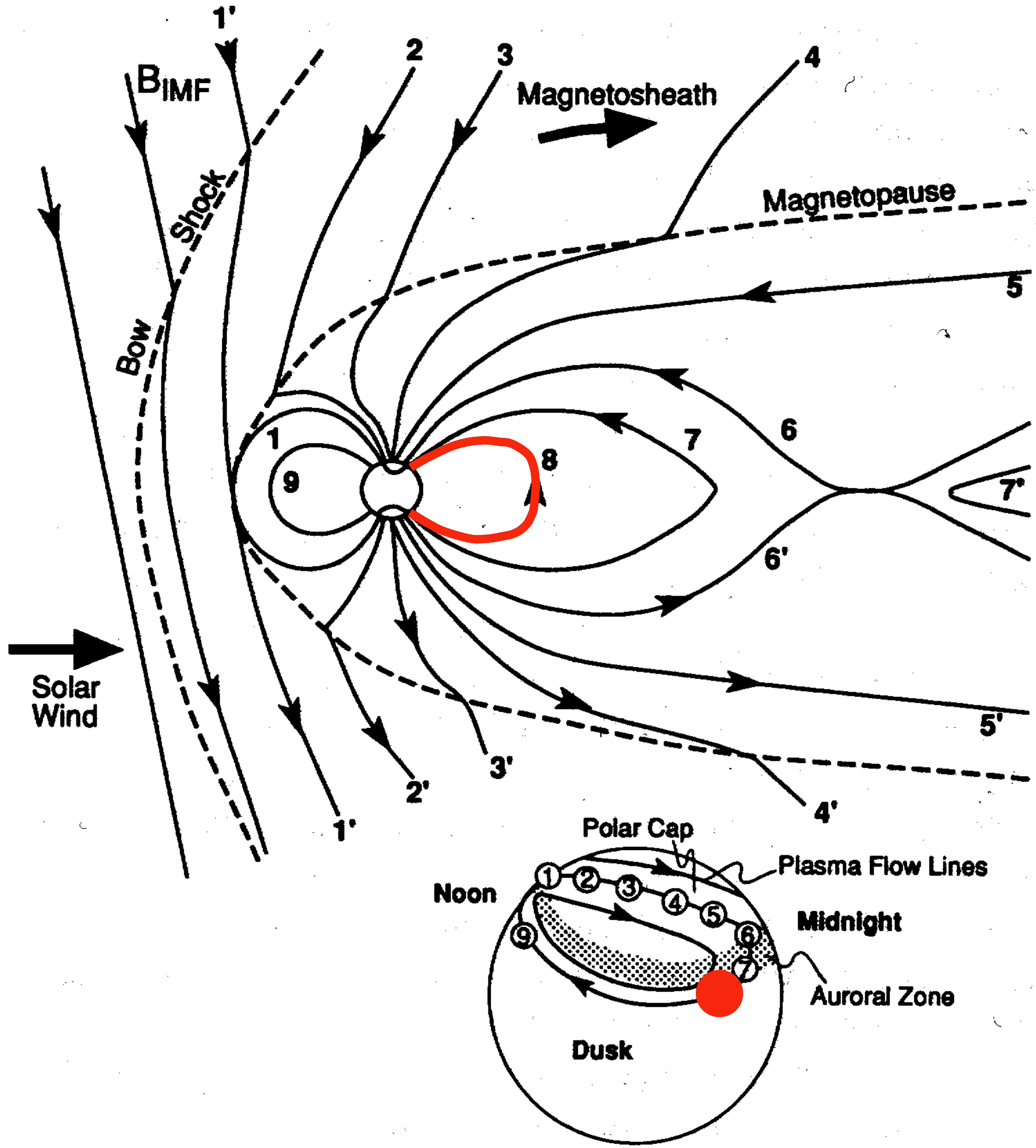
2nd reconnection in current sheet



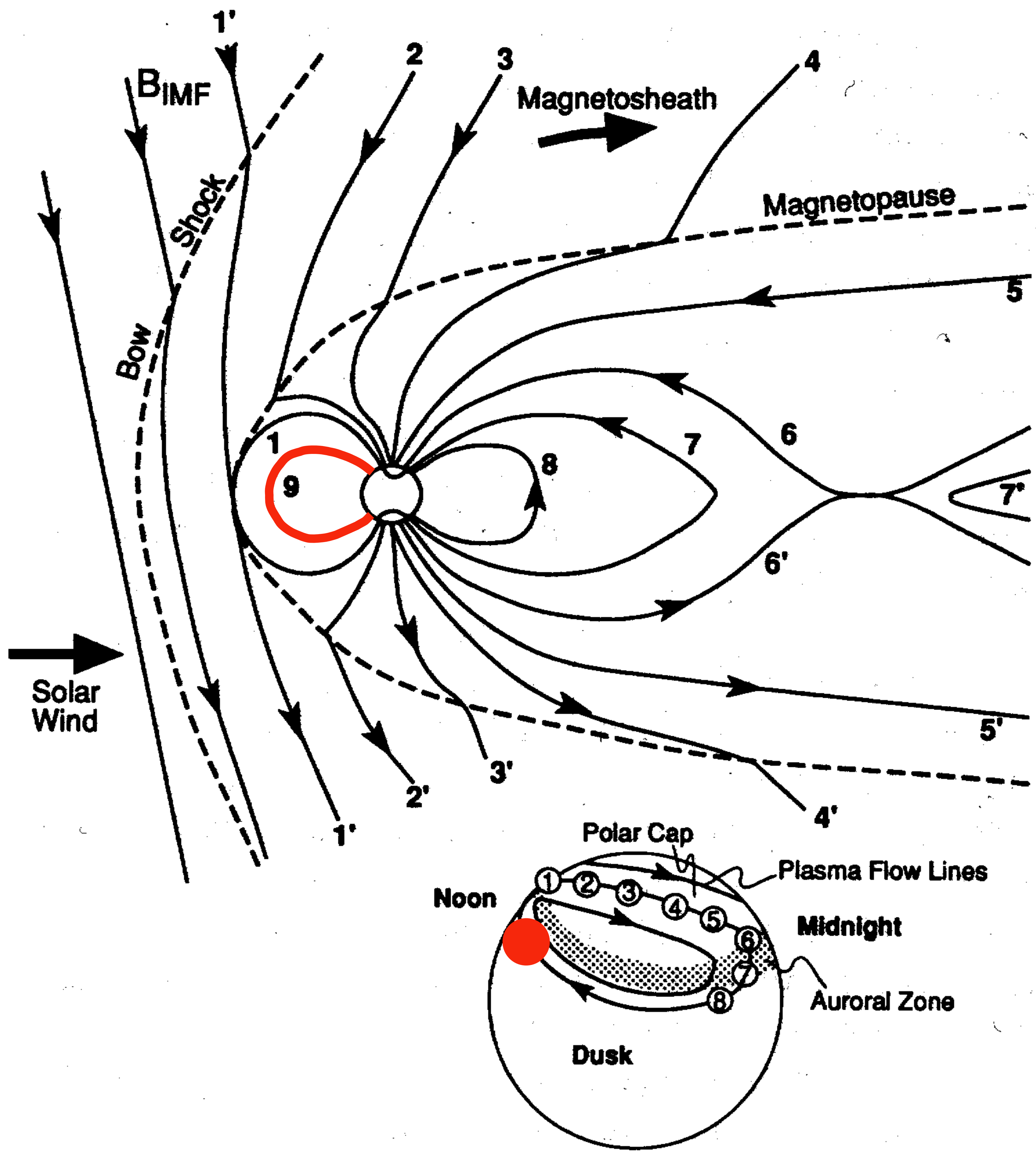
tailward plasmoid ejection



dipolarisation of magnetic field



dayside return of magnetic flux



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Then transport day ➔ night, followed by 2nd reconnection in magnetospheric tail (= substorm)

In the magnetotail, study of reconnection in the frame of a "Harris" current sheet equilibrium = symmetrical conditions on both sides of current layer / reconnection site

Study of the Magnetopause situation is more complex : N,T,B differ by up to ~1 order of magnitude / current layer

➔ parametric study via a hybrid code (ions = PIC, e^- = fluid ensuring neutrality [Ohm's law])

➔ difficulties of PIC simulations : initial distribution function & boundary conditions